An Investigation into the Data Collection Process for the Development of Cost Models

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ABSTRACT

This thesis is the result of many years of research in the field of manufacturing cost modelling. It particularly focuses on the Data Collection Process for the development of manufacturing cost models in the UK Aerospace Industry with no less important contributions from other areas such as construction, process and software development.

The importance of adopting an effective model development process is discussed and a new CMD Methodology is proposed. In this respect, little research has considered the development of the cost model from the point of view of a standard and systematic Methodology, which is essential if an optimum process is to be achieved. A Model Scoping Framework, a functional Data Source and Data Collection Library and a referential Data Type Library are the core elements of the proposed Cost Model Development Methodology. The research identified a number of individual data collection methods, along with a comprehensive list of data sources and data types, from which essential data for developing cost models could be collected.

A Taxonomy based upon sets of generic characteristics for describing the individual data collection, data sources and data types was developed. The methods, tools and techniques were identified and categorised according to these generic characteristics. This provides information for selecting between alternative methods, tools and techniques.

The need to perform frequent iterations of data collection, data identification, data analysis and decision making tasks until an acceptable cost model has been developed has become an inherent feature of the CMDP. It is expected that the proposed model scoping framework will assist cost engineering and estimating practitioners in: defining the features, activities of the process and the attributes of the product for which a cost model is required, and also in identifying the cost model characteristics before the tasks of data identification and collection start. It offers a structured way of looking at the relationship between data sources, cost model characteristics and data collection tools and procedures. The aim was to make the planning process for developing cost models more effective and efficient and consequently reduce the time to generate cost models.

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DECLARATION

I declare that the work described within this thesis was undertaken by myself, Ysolina Delgado-Arvelo, for the degree of Doctor of Philosophy at De Montfort University. It has not been submitted in part or whole for any other degree or qualification at this or any other academic institutions.

It is the result of my own effort unless otherwise stated.

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LIST OF ABBREVIATIONS

AACEI: Association for the Advancement of Cost Engineering International

ABC: Activity Based Costing

ADC: Automated Data Collection

AHP: Analytic Hierarchy Process

CAD: Computed Aided Design

CEH: Cost Estimating Handbook

CEM: Cost Estimating Model

CER: Cost Estimating Relationship

CET: Cost Estimating Time

CMDP/CMP: Cost Model Development Process/Cost Modelling Process

CMSF/MSF: Cost Model Scoping Framework/Model Scoping Framework

CNC: Computer Numerical Control

CPA: Critical Path Analysis

DC TTMs: Data Collection Tools, Techniques and Methods

DCT: Diagramming and Charting Techniques

DDF: Double Diaphragm Forming

DFM: Design for Manufacturability

DoE: Department of Energy

DoD: Department of Defence

DS: Data Sources

Dtypes: Data Types

EDI: Electronic data interchange

ERP: Enterprise resource planning

ERMP: Engineering Research and Management Practices

ESMM: Exploratory Sequential Mixed-Method Research Methodology

EsT: Estimating Techniques

GAAP: Generally Accepted Accounting Principles

GAO: U.S. Government Accountability Office

IDEF: Integration DEFinition modelling methods

IEEE: Institute of Electrical and Electronics Engineers

IRR: Internal Rate of Return

LCC: Life Cycle Costs

MODAPTS: Modular Arrangement of Predetermined Time Standards

MOST: Maynard Operational Sequence Technique

MRP: Material Requirements Planning

MRP II: Manufacturing Resource Planning

MSF: Model Scoping Framework

MTM: Methods Time Measurement

NASA: National Aeronautics and Space Administration

NPV: Net Present Value

NPI: New Product Introduction

OCR: Optical Character Recognition

PC: Paired Comparison

PERT: Program (or Project) Evaluation and Review Technique

PDP: Product Development Process

PMTS: Predetermined Motion Time Systems

SFDC: Shop floor Data Collection

SIG: Special Interest Groups

SRT: Survey Research Techniques

TCM: Total Cost Management

TER: Time Estimating Relationship

TTM: Tools, Techniques and Methods

TWC: Team Working and Consensus Techniques

USPTO: United States Patent and Trademark Office

VSM: Value Stream Mapping

WBS: Work Breakdown Structure

WIP: Work in Progress

WDME: Work Design and Methods Engineering

CHAPTER 1. INTRODUCTION

This research investigation examines two essential areas for the success of the Cost Model Development Process (CMDP) in assisting industrial businesses to achieve and attain competitive advantage, namely: the need for a coherent and standardised approach for developing cost models and the problems associated with the data identification and data collection tasks, including availability of historical cost information, lack of process and product expertise and effective tools and methods to gather cost data.

One of the main objectives of this investigation is to provide a step change in the time and resources required to develop cost models by reviewing current cost model development practices and building a more efficient and coherent Cost Modelling Methodology.

In addition, this work is focused on the development of an effective and structured Model Scoping Framework, to be integrated into the proposed model development procedure for identifying the different elements and sources of data and information required for building cost models, and most importantly, in the identification of efficient tools and techniques for cost data collection. Both are essential to the success of the CMDP.

1.1 Research Rationale

Experts suggest that adding value is the key attribute that will develop and maintain UK manufacturing competitiveness against the strong competition from economies known as Low Cost Countries (LCC) (Kim and Arnold, 1996; Pullin, 2006; Ross, 2004).

Porter (1985) emphasises technological change as a primary force behind competitiveness and suggests that new technology impact should be measured against the requirements of global markets. A projection of these market requirements onto the manufacturing context exposes characteristics such as low manufacturing costs, high process quality, short process lead times, process flexibility and environmentally friendly product designs and processes. New technology should impact positively on these factors.

The rapid technological advances, along with other increasing market pressures have increased the demand for higher product complexity and functionality (Rush and Roy, 2001a). As a result, UK industry needs to improve their business and manufacturing operations and identify and develop core competencies by addressing industry and customer requirements. These requirements have been widely discussed in the literature (Bode, 2000; Chin-Fu Ho, 1996; Dangayach and Deshmukh, 2001; Kumar and Motwani, 1995; Sin-Hoon and Lay-Hong, 1996; Shehab and Abdalla, 2001, 2002a and 2002b; Shu-Hwa, 2002; Spring and Dalrymple, 2000; Waldron, 1999; Wang, 2000) and are summarised in Figure 1.1.

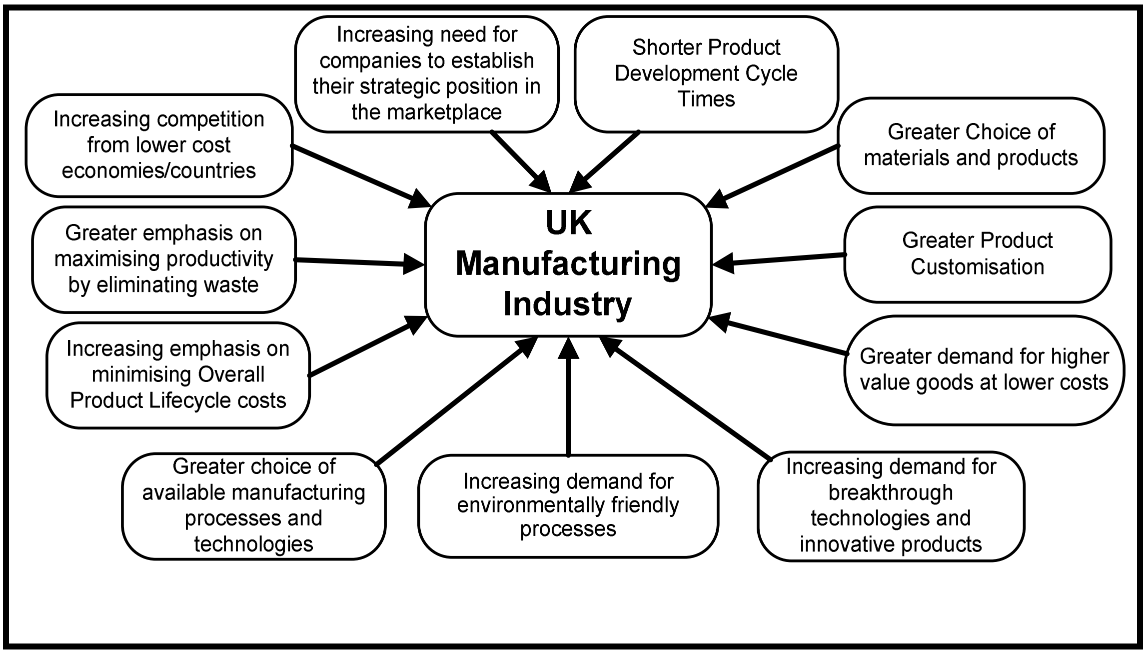


Figure 1.1 Customer and Industry Requirements to be addressed by the UK Manufacturing Sector (Developed Work).

This market situation (Figure 1.1) has significant effects on the cost estimating process, where cost models play an important role by providing process times and cost information (Wang et al, 2000b). The main changes occurring in the CMDP, as a consequence of the market requirements, are summarised in Table 1.1.

In order to cope with these requirements, it is imperative that the cost modelling process (CMP) becomes more responsive and structured (Oduguwa, 2006). It is expected an increase in the required number of new cost models in order to support the implementation of manufacturing strategies, to face global competition and to meet new customer demands (Baguley, 2004). These new cost models must be rapidly generated, more accurate, comprehensible and accessible to a wider pool of users from a variety of business functions.

The Cost Modelling Process frequently requires high levels of resources to achieve satisfactory outcomes. Of particular concern is the lack of consistency between the cost model characteristics, defined at the concept stage of the development process of the model, against the actual outcome, i.e. the final cost model. These discrepancies cause having to go around the CMP loop more times than what it is actually necessary. In addition, there are limitations to the availability of effective techniques and tools for 'enabling' experienced cost practitioners to choose and make use of appropriate cost modelling practices (Curran et al, 2005). Significant deficiencies are those related to the main tasks involved in the data identification, data collection and data analysis required for the cost models.

Changes affecting the Cost Modelling Process	Reference
Greater need for more efficient and formalised data identification and collection methods for reducing the development time of models.	Stockton et al (2000a) Liyanage and Perera (1998) Perera and Liyanage (2000, 2001)
Increasing demand for cost models developed during the early design stages of the product development process, as a necessary step towards optimising product cost, providing quicker quoted price service for customers and making the mass customisation production more efficient.	Stockton and Wang (2004) Xu, Fang and Gu (2006) Bode (2000)
Greater need to produce cost models flexible enough to cope with uncertainty and risk, as when new products and technologies are involved.	Colmer et al (1999) Neumann (2002) Roy et al (2001)
Increasing need for higher estimating reliability, precision and accuracy within the cost model development process, particularly when models for potentially competitive products are required.	Lederer and Prasad (1992, 1993, 1995) Elgh and Cederfeldt (2008) Cheung et al (2009)
Increasing demand for greater numbers of predictor variables within cost models, especially when the availability of historical data and process expertise are limited or poor and when the product development cycle times are becoming increasingly shorter.	Baguley (2004) Roy, Rush and Tuer (2002) Koonce et al (2003)
Increasing demand to produce cost models with different levels of detail earlier in the product development process, and with the proper amount of input data consistent with the project stage or process/product definition at the time when cost estimates have to be generated	Scanlan et al (2002) Rush, Falque, and McRitchie (2001) Meisl (1988)
Greater need for cost models in support of cost reduction strategies including: Identifying non-manufacturing and non-value added activities New product line introduction Expanding initiatives into new market places (including complying with local regulations).	Curran et al (2003) Rush and Roy (2000)
Increasing need for cost models build in line with the business function and objectives they are primarily conceived to serve.	Daschbach and Apgar (1988)
Greater demand for costing data sources made available to the cost engineering community form other business functions as products and processes are becoming the result of multifunctional efforts and teamwork approaches.	Roy et al (2001); Curran et al (2005) Schonberger and Knod (1994)

Table 1.1 Main changes occurring in the Cost Model Development Process (Developed Work)

These problems are caused, to some extent, by a lack of consistent and structured developing procedures and framework for:

- Outlining the cost model purpose to clearly define the business objectives and functions the model is due to serve and support.

- Identifying the relationship between the cost model characteristics, tools and methods to effectively and efficiently identify and collect the appropriate data.
- Mapping the stages involved in the cost modelling process, including identification of involved resources, information sources and data owners.

Initiatives and strategies to face these issues and improve the cost modelling process will ultimately result in improving the product development process and its outputs (Bashir and Thomson, 2001). These initiatives and strategies should aim to reduce the waiting times for cost estimates which cause downstream delays in the product and process development times (Farineau et al, 2001).

Figure 1.2 shows that approximately 70% to 80% of the total product cost is committed based upon decisions taken during the first 20% of the product development process. This corresponds with the concept formulation stage, when product information is not yet available in detail; thus, difficulties arise in making accurate cost estimates (Bode, 1998; Daschbach and Apgar, 1988; Guenov, 2002; Rush et al, 2001).

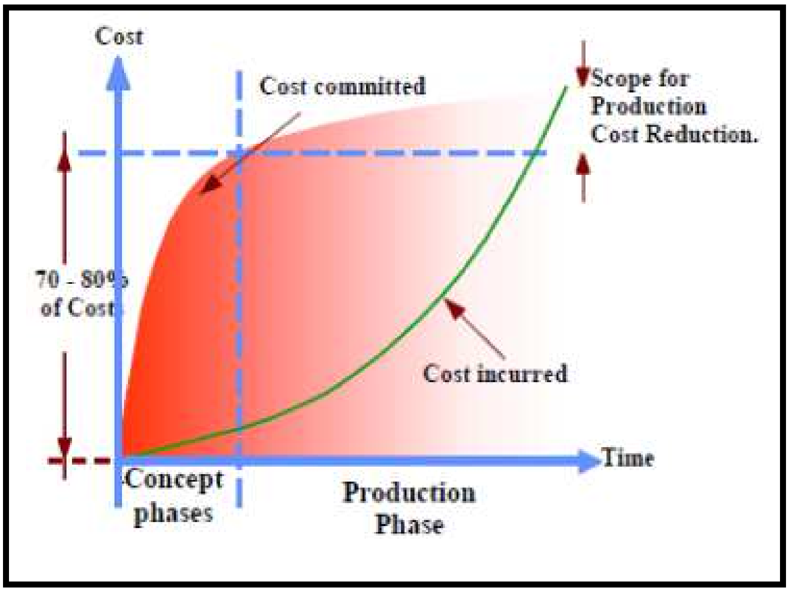


Figure 1.2 Cost Commitment Curve. (Rush et al, 2001)

One of the greatest challenges is that providing top level cost estimates at the conceptual product design phase relies not so much in building an adequate model, but providing meaningful input data for the model (Meisl, 1988). There is a high degree of uncertainty during the early stages of product development, and consequently a significant estimating error (Rush et al, 2001). The main causes of uncertainty arise from working with a limited amount of available data related to the product or process, lack of consistency and reliability from the data that is available, issues concerning the cost model requirements and assumptions, and risk considerations.

The effect of lack of cost data and information early in the cost modelling and estimating process is graphically illustrated by the Freiman curve (Figure 1.3). Underestimates lead to financial loss. Overestimates jeopardise the opportunity to produce and deliver a good product or service for a realistic price (H'mida et al, 2006). The most economical cost (i.e., lower development cost) comes from meaningful, complete, and realistic estimates at the early development phases.

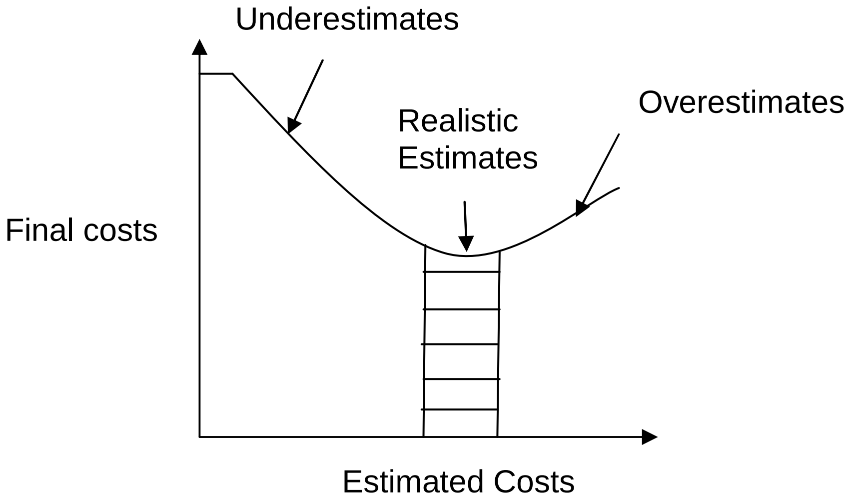


Figure 1.3 The Freiman Curve. (Daschbach and Apgar, 1988)

A study by Lederer and Prasad (1992) on cost estimating practices at 115 organisations found that only around one in every four projects as completed at a final cost reasonable close to its estimate.

Guenov (2002) ascertains that one particular need has been to provide tools that could assist *'high level decision makers'* in comparing alternatives '*on the basis of cost, value, performance (effectiveness) and technical risk'* so that they can gain and sustain competitive advantage over their market rivals.

Consequently, it is paramount to be able to accurately estimate cost at the concept stage of the product development process. Nevertheless, there is yet a basic need for tools which would help and support engineers, managers and decision-makers in general in reaching reasonable and measured design decisions that are not only cost-effective but also, more competitive.

Meisl (1988) calls attention to the importance of meaningful input data for the model in order to produce reliable and accurate cost estimates. The author also mentions that independently from the method being used to build the model and the level of detail required for the input, the cost engineer has to be 'resourceful' in order to comply with the model input requirements in relation to:

- Finding the right data source,
- Appropriately enquiring for cost information and asking the right questions,
- And ultimately transforming the cost data, expert responses and cost information into model inputs.

Meisl (1988) also suggests that by using available approaches from Operations Research, Behavioural Science, Psychology, and Interviewing Methods, modified to adapt specifically to cost modelling and estimation, limitations associated with the identification of appropriate sources of data and the collection of the information to build the cost model can be greatly assisted.

1.2 Background of the Research

This research investigation builds on the work initially conducted as a three year EPSRC funded research programme entitled COSTMOD: Improving the Cost Model Development Process (Stockton et al, 2000b and 2002).

During the project, a structured approach to traditional development procedures was proposed, the COSTMOD methodology. This consisted of more defined tasks, and reduced the model development procedure down to four main areas linked to an expert advisor (Figure 1.4). The main body of research for this thesis is the model scoping and data collection stage within the overall development process.

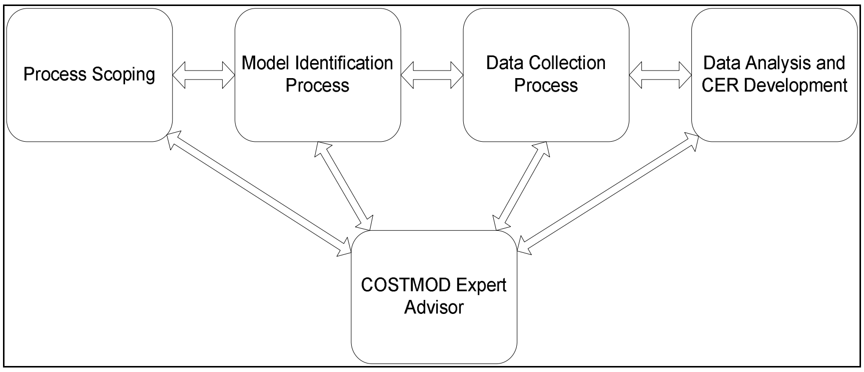


Figure 1.4 COSTMOD Development Procedure (Stockton et al, 2002)

1.3 Research Aim and Objectives

The primary aim of this research is to improve the data collection process in the generation of cost models by, firstly, examining the Cost Modelling Process in terms of the data sources and data collection tools and techniques used when producing cost models and estimates; and secondly, by establishing how the appropriate selection of these elements can contribute to make cost model generation faster, easier, structured and accurate.

These aims will be accomplished by achieving the following Research Objectives:

- Identify methods and tools in place for the identification of product and process features, process activities and associated cost drivers in the CMDP.
- Investigate the factors which influence the selection of data collection tools and techniques, and data sources in the development of cost models.
- Investigate the relationship between cost model characteristics and data collection tools and data sources.
- Review current cost model development practices to identify the sources of waste in the process and to propose a more efficient and coherent Cost Modelling Methodology.

The main contribution to knowledge of this research work consists of:

- A new Cost Model Development (CMD) Methodology.
- A Model Scoping Framework (MSF), to be integrated into the Cost Model Development (CMD) Methodology.

The final benefits of this work include bringing visibility, accuracy, time efficiency and structure to the process of developing cost models.

As a result of different constraints, the scope of the research was limited to the aerospace manufacturing industry with some contributions from other areas including construction, process and software development. However, the applicability of the research outcomes in other areas as well as contributions from other domains, including design engineering, could be investigated as part of further work.

1.4 Research Methodology and work undertaken

In order to achieve the research objectives and to answer the research questions (Table 1.2), an Exploratory Sequential Multi-Method (ESMM) research model was adopted (Sharkey and Sharples, 2001).

The new CMD Methodology and the Model Scoping Framework (MSF) presented in this work have evolved through a combination of literature review, focus group discussions, interviews, company visits, and two survey questionnaires (Table 1.2). The data gathered from these methods was analysed using qualitative and quantitative tools including Cause-effect diagram, Pareto Analysis, Descriptive Statistical Analysis, Paired Comparison Analysis, and Case Study.

Stage	Research Questions	Methods
EXPLORATION	-What is the nature of the Cost Modelling Process? -Identify current needs/gaps within the CMP data collection task	-Literature review -Observation -Semi-structured Interviews -Survey Questionnaire I -Qualitative Analysis
FORMULATION	-What is the nature of Data Sources and Data Collection tools in the Cost Modelling Process? -What are the factors influencing the cost model characteristics within the CMP and sources of waste	-Survey Questionnaire II -Follow-up Semi-structured Interviews -Focus Group Exercises/Small Group Discussion -Qualitative and Quantitative Analysis
EVALUATION and VALIDATION	-How can the Cost Modelling Process be improved? -How can the Data Collection Task in the CMP be improved?	-Proposed CMP Methodology -Refined Library of methods and tools (DC-TTMs) -Proposed CMP Scoping Framework -Process Scoping Framework Trials -Validation of the proposed CMP Methodology.

Table 1.2 Overall Methodology and work undertaken (Developed Work)

The Evaluation and Validation phases of the ESMM research methodology included the validation of the effectiveness of the Cost Modelling Methodology and the verification of the appropriateness of the Model Scoping Framework (MSF) tool in gathering information related to the manufacturing process involved as well as information necessary to determine the cost model characteristics.

The validation of the Methodology was accomplished via a case study and the verification of the Model Scoping Framework, was carried out via industrial trials and internal exercises on existing and new models for manufacturing processes and products at different development stages at the industrial collaborators and participants in the research.

1.5 Main Research Outcomes

The new proposed CMD Methodology emphasises on the initial stages of the cost modelling process, i.e., data identification and collection of input data.

Another contribution, no less important, it is the Model Scoping Framework as a structured way of looking at the relationship between data sources, cost model characteristics and data collection tools and procedures, aiming to make the planning process for developing cost models more effective and efficient and consequently reducing the time to generate cost models.

The present investigation builds and extends on Meisl's suggestion (Section 1.1) by incorporating the selection of data collection tools and techniques, as part of the new proposed CMD Methodology, from a broader spectrum which includes: Diagramming and Charting Techniques (DCT); Work Design and Methods Engineering (WDME); Estimating Techniques (EsT); Team Working and Consensus (TWC) Techniques; Survey Research Techniques (SRT) and Engineering Research and Management Practices (ERMP). The techniques, tools and methods (TTMs) were analysed and grouped into categories based on their similarities in approach, input information, output information, and scope among other features.

This guided the refinement of a library of data collection tools, techniques and methods (DC-TTMs) through a combination of survey questionnaires, interviews with cost engineering and estimating experts, focus group exercises, and extensive literature review. A Library of data types for specific processes was also created using the input from manufacturing processes utilised at the participant organisations.

1.6 Thesis Structure

Chapter one is a brief introduction to the research work, which include a description of the reasons and justifications that are the basis for this investigation; the research background; research aims and objectives; research methodology and outcomes; and thesis structure.

The Literature review consists of two chapters. Chapter Two describes in detail the cost modelling process, its stages and characteristics, benefits and limitations.

Chapter Three develops the subject related to the use of information in the cost modelling process, including the description of common and new sources of costing information, data types and their levels, data collection tools and techniques, and the factors affecting the selection of appropriate information sources and data collection methods.

Chapter Four fully describes the research methodology, as well as the scope of the investigation and the methods employed to carry out the research.

Chapter Five describes the results from the Exploration and Formulation phases of the research methodology, and the analysis and discussion of those results from the literature review, survey questionnaires and interviews, and focus groups.

Chapter Six represents the Evaluation and Validation stages of the research methodology. It outlines the Proposed CMD Methodology and the Model Scoping Framework (MSF) built within it. The Chapter describes the validation of the Methodology via case study and the verification of the MSF using industrial trials, on models for product/processes at different development stages. It also contains the analysis and discussion of results from the case study and trials.

Finally, Chapter Seven discusses the main conclusions and the recommendations for further work.

CHAPTER 2. DEVELOPMENT OF COST MODELS

2.1 Introduction

Cost models are an important component in the cost estimation process, as they provide cost information necessary to justify, validate and support estimates. As a methodology, Cost Modelling combines scientific theory, engineering principles and established commercial practices for simulating and estimating the cost of new technologies (Busch, 1994).

In the first part of this chapter, the fundamentals and some key issues of cost estimating and cost modelling are examined and discussed. The second part describes the Cost Modelling Development Process, including the phases and tasks involved; the cost model characteristics and methods; and the importance, limitations and influential factors affecting the development process. It then looks at cost estimating and modelling approaches and methodologies. The discussion then focuses on the proposed development approach that aims to address the research gap.

2.2 Cost Estimating and Cost Modelling

The fundamentals of cost estimating have been widely documented by many authors including Ostwald (1992), Stewart et al (1995), Winchell (1989), Creese et al (1992), Matthews (1983), Park (1973), Clugston (1971), and Skitmore and Marston (1999).

Costing implies the allocation of expenditure to various stages of the production process; for example, fixed costs including rent insurance and depreciation and variable costs such as direct labour and material and some overhead costs (Innes et al, 1994).

Life Cycle Costs (LCC) are the total costs incurred by a business for the acquisition and ownership of a product or asset (machinery and equipment) over the life of the asset, including research and development, fabrication and testing, operation, maintenance, conversion and/or decommission (Park et al, 2002). LCC are summations of cost estimates from launch ('cradle') to disposal ('grave') for products, equipment and projects (Woodward, 1997).

Estimating is defined as the approximate calculation of a value, amount, or time, which is based upon judgement, experience, skills and achieved by using the necessary data, rules and tools. The cost estimating process can be defined as the set of steps that take place to calculate the expected cost of a resource, namely, labour, material, overheads, among others (Ostwald, 1992). The AACEI Total Cost Management (TCM) Framework (AACE International, 2006) defines cost estimating as *“the predictive process used to quantify, cost, and price the resources required by the scope of an investment option, activity, or project.[...] applied during each phase of the asset or project life cycle as asset or project scope is defined, modified, and refined”* (AACE International, 2006:50). In manufacturing, this definition implies the economic evaluation of a given design or product, and the outcome of the process, i.e. the cost estimate is expressed as a cost, amount or value.

A model is a representation or description designed to show the main purpose and to explain or predict some aspects of the reality behind an object, design, system, or concept. They are used not only in the natural sciences and in the social sciences but also, and most extensively, in engineering disciplines, including cost estimation and cost modelling. The AACEI Total Cost Management (TCM) Framework (AACE International, 2006) defines cost models as costing algorithms which transform *‘project technical’* and ‘*programmatic descriptive information’* into cost and resource terms (AACE International, 2006). Resource requirements (quantities of resources such as labour, material, and equipment) are the outputs of the estimating quantification process and costing algorithms (namely, CERs or cost models) and are used as a basis for resource planning and procurement.

According to Ostwald (1992), cost estimates can be classified according to a variety of criteria including: purpose, accuracy, time, and design. A tabular description of this classification has been adapted and presented in Table 2.1.

The author points out that the estimating methods used in each category might be different from those required for other types of estimates. In the same way, he argues that the output from an estimate becomes the input of another estimate at a higher level.

Another common cost estimating classification is based upon the order of magnitude or ‘dollar value’ of the estimate. In the early stages of the product design development process, ‘order of magnitude’ estimates are produced, as there is not enough data available. Later in the process, as more information is generated and made available, estimates become more accurate and detailed. The more accurate the estimate, the more time spent in its preparation and the more design data that is required and that must be generated prior to making the estimate.

Design	Fundamental Characteristics	Economic Measure	Examples
Operation	Content: way of working Estimate: labour forecast and material required for an operation design (direct/indirect labour; direct/indirect material)	Pound/dollar Cost Man-hour; man-days	Assembler & hand tool; driver & transportation vehicle; admin worker in an office
Product	Design change and production quantity	Price	CNC machine tools, transportation vehicles, turbines, computer hardware
Project	Single end item; only one to be manufactured or constructed The design is perhaps custom, and usually requires a significant period of time for manufacture or construction	Bid value The pound/dollar amount is considered capital (large) rather than expense (minor)	Capital tooling, bridge, plant addition, special purpose building, refinery, prototype
System	Design and configuration of operations, products and projects in any arrangement. Public, government, not-for profit enterprise domain	Effectiveness; Benefit-Cost; Budget-fiscal period total;	Systems of machine and people: Weapon system; Hospital; Rapid transit system

Table 2.1 Classification of Estimates (Ostwald, 1992)

Based on the level of detail and accuracy, Park (1973) proposes three types of estimates, namely: order of magnitude estimates, semi detailed or conceptual estimates and detailed estimates.

Ostwald (1992) maintains that despite varying with the stage in the design PDP in their level of detail, accuracy and other characteristics, the intellectual requirements for any of those estimates should remain the same. However, evidence from developed work shows that the required expertise and skills to produce detailed models increase with the level of detail and complexity, and call for new players with high level of process or product knowledge and specialisation. Furthermore, different cost models and approaches are required and used throughout the several stages of the PDP. Consequently, any one project may call for cost models and estimates each developed by a number of cost practitioners with different levels of expertise and specialism.

As pointed out by Curran et al (2004), Cost Modelling may be a particularly complex field to evaluate in terms of scientific theory. The authors argue that Cost Modelling is perceived as an attribute of design or manufacturing decisions or even a product rather than an established scientific field.

2.3 Applications of Cost Models

Cost models are useful tool for estimating the development and production cost of products including spacecraft, space transportation systems, aircraft missiles, ships and land vehicles. In the aerospace industry, cost models provide a range of key business processes with essential decision-making information. This is especially important for the selection of material, new products or technology; for the evaluation of program alternatives; for understanding impacts of design features and for the identification of factors with the greatest impact upon cost (*'economic bottlenecks'*) within a particular technology (Busch, 1994).

Cost models are tools for cost estimation in the early stages of PDP, when 80% to 85% of the product's whole life cycle costs are committed. They are also a main component and a starting point of product life cycle cost management. Knowledge of costs and cost behaviour are essential for effective decision-making. Cost models supporting product and process estimates have gained an important role since they are useful instruments to obtain process and cost information.

They are useful for identifying opportunity windows for process and product improvements; highlighting problems related to design and tooling; maximising productivity and eliminating waste. Decisions on product variations, the use of standard parts, distribution channels, make or buy, and lot size, often involve trade-offs between product cost structures and market required performance characteristics. Accurate cost models will inform such trade-off by combining the different productivity measures in a specific cost metric (Daschbach and Apgar, 1988).

Cost models have been developed for a variety of applications and purposes, including for example supporting the product development process by:

- Analysing and Managing Complexity related to product variety in Automotive Production (Schleich, Schaffer and Scavarda, 2007)
- Supporting the decision making process when selecting cost effective Composite Manufacturing Processes and Technologies (Gutowski, 1994)
- Solving cost estimation problems of plastic injection products at the development stage (Wang, 2007)

- Assisting the decision making process for project selection and bidding (Jiang et al, 2003)

2.4 Cost modelling platforms and techniques

Cost models are built using a variety of approaches and techniques which can classically be informal and decided on the judgement and experience of the cost modelling practitioner (cost engineer or estimator); and agreed with the product and manufacturing teams involved in the model generation process. These cost modelling tools are required to guide cross-functional and multidisciplinary teams in the decision making process (DMP), although it is widely acknowledged that it is extremely difficult to obtain fast and accurate cost estimates (Curran, 2005).

The Cost Modelling literature is based around cost estimate generation (Lederer and Prasad, 1992). Several methods used to produce cost or time estimating relationships were identified from the Literature review including the work by Curran et al (2003, 2004 and 2005); Watson et al (2006); Datta and Roy (2009); Ostwald (1992), Stewart et al (1995), Winchell (1989), Creese et al (1992), Matthews (1983), and from interviews with industrial and academic cost engineering practitioners.

A variety of cost estimating techniques is available. The two ends of the estimating spectrum (Table 2.2) are Parametric Estimation (offering a macro system approach and used to build high level cost models) and Detailed Grass Roots Estimation, also known as Bottom Up, Engineering Build-Up or Detailed Estimating (offering a micro system approach and used to construct low level cost models).

Lifecycle Phases	Parametric	Bottom Up
Definition / Conceptual	√	
Development	√	√
Prototype/Verification	√	√
Production	√	√
O&S/Commercial	√	√

Table 2.2 Applicability of Estimation Techniques along the Lifecycle Phases (Developed Work)

In between, the most common engineering cost estimating techniques are Top Down, Rule of Thumb, Analogy, Case Based Reasoning, Parkinson, Expert Judgement, Detailed Unit Cost, Price to win and Equipment Factored Estimation. Roy (2003) and Price et al (2006) identify Bottom Up, Feature Based, Design to Cost, Analogy, and Parametric as the main approaches involved in manufacturing cost estimating. Table 2.3 lists some of the most common estimating techniques used in three of the main industry domains identified from the literature, surveys and interviews with process and modelling experts.

Estimating Techniques	Manufacturing Aerospace	Building Industry/Capital Projects/Construction	Software Development and Products
Top Down	√		
Rule of Thumb	√		
Analogy	√	√	
Parametric	√	√	√
Bottom Up/ Detailed Grass Root/ Detailed Estimating	√		
Parkinson	√		
Expert Judgement	√	√	√
Detailed Unit Cost		√	
Equipment Factored Estimation		√	

Table 2.3 Cost Estimating Techniques used in the Main Manufacturing Sectors (Adapted from Shabani and Yekta, 2006; Curran et al, 2006)

Based on their nature, the modelling techniques could be grouped into three main basic categories, namely, Non-Algorithmic Methods, Algorithmic Methods and Cost Accounting Methods. This classification offers a broader approach for allocating the vast variety of methods independently of the industry in which they are applied and their purpose, accuracy, details level or context application.

Among the Non-algorithm Methods, some researchers observe that, in practice, the most common cost estimating method is estimation by analogy. Algorithm Methods involve the application of one or more mathematical formulas or cost models, which generally have been derived through statistical data analysis (Angelis and Stamelos, 2000). The most common of the methods under this classification is parametric modelling.

Cost accounting methods are used to support the decision-making process to reduce company's costs and improve profitability. They are not modelling methods per se; however, they are used for financial planning, budgeting and determining actual cost of operations, processes, departments or product and the analysis of variances, profitability or use of funds.

During a cost estimating or modelling exercise, these procedures are applied to the basic cost or process time to obtain the final cost estimate. There are various cost accounting approaches, also refer to as *Generally Accepted Accounting Principles (*GAAP*),* including Standardised or Standard Cost Accounting, Lean Accounting and

Activity Based Costing (ABC). Other methods involve Resource Consumption Accounting, Throughput Accounting, Marginal Costing (Cost-Volume-Profit Analysis).

The research in ABC is extensive with an important proportion of this research focusing on the manufacturing industry (Cooper and Kaplan, 1991). ABC is a full analytical costing method that aims to allocate costs, and where activities (process tasks and operations), resources (activities consumables), and cost drivers are the essential concepts (Macheridis, 2004; Sun et al, 2007). Nowadays, industry in general has understood that the approach could also be used for cost engineering (Roy, 2003).

There are other cost estimation tools commercially available. Software based cost estimation tools employ one or more of several known methods, including parametric modelling (Briggs et al, 2005), knowledge-based modelling (Abdullah et al, 2002; Serpell, 2004), rule induction (Weiss and Indurkhya, 1993), fuzzy logic (Huang et al, 2007; Xu and Khoshgoftaar, 2004), dynamic modelling (Bond and Meghir,1994), expert judgement (Hughes, 1996; Rush and Roy, 2001b), artificial neural networks (Stockton and Wang, 2004; Wang, 2007), genetic algorithms (Kim et al, 2004; Li et al, 2009) or case-based reasoning (Duverlie and Castelain 1999); and data storing techniques such as data mining and on-line analytical processing (OLAP).

Current research into cost modelling focuses on neural networks and case-based reasoning methods along with a few architectural approaches (Baguley and Roy, 2007).

Some of the commercial and proprietary cost estimation tools whose algorithms, relationships and interfaces are publicly available, well defined, and parameterised include COCOMO II, ACEIT, Construx Estimate, COSMOS, COSTAR, Cost Xpert, , ESTIMATE Pro, PRICE-S, SEER-SEM and SLIM-Estimate. Most tools have some kind of interface to external applications such as Microsoft Excel, used primarily for data input and output.

2.5 Resources that can be costed and estimated

From an accounting point of view, the pattern of expenditures (resources) to be estimated or costed is generally Material Costs, Labour Costs and Overhead Costs (Creese et al, 1992). There is also an economical classification that breaks down costs into Direct and Indirect Costs (H’mida et al, 2006).

Curran et al (2004 and 2007) and Price et al (2006) review the current advances in engineering cost modelling as applied to the aerospace industry and describe recognised definitions of cost that relate to the engineering domain. In addressing the literature, the authors explain various cost resources and categories recognised as being incurred during the manufacturing process of an aircraft, including Recurring and Non-recurring Costs, Fixed and Variable Costs, Direct and Indirect Costs and Lifecycle Costs.

The above categorisations are all well documented and explained in the cost modelling and estimating literature (Cooper and Kaplan, 1991; Creese et al, 1992; Leung and Fan, 2002; Niazi et al, 2006; Ostwald, 1992; Stewart et al, 1995; Shuford, 1995; Winchell, 1989) and most accounting references will again use these categories to explain the different types of costs, their interpretation and most importantly, their allocation as to what activity in the production process or resource they are associated with. Cost allocation can be defined as a method or a combination of methods that results in a reasonable distribution of costs (Stewart et al, 1995).

Total product costs in manufacturing are composed of different combinations of several of the above cost items. Different breakdowns of product costs are available in the literature (Asiedu and Gu, 1998, Cooper and Kaplan, 1991, Liebers and Kals, 1997; Hundal, 1997; Sun et al, 2007; Winchell, 1989). A general cost breakdown structure appears to be hardly possible. The classification and allocation of resources and associated costs will ultimately depend on the costing system and the business approach that each particular industry follows.

2.6 The Cost Model Development Process

The Cost Modelling Process (CMP) concerns the identification and collection of product, process and cost information, which is then analysed to estimate a cost or time (Ostwald, 1992). The process essentially consists of a series of sequential data collection, data identification, data analysis and decision making tasks, whose main function is to identify the potential cost drivers or predictor variables for the construction of mathematical models. These models are usually statistical regression equations, known as cost estimating relationships (CERs) and time estimating relationships (TERs), that mathematically describe project, process or product costs (Ogunlana, 1989). Figure 2.1 illustrates a traditional Cost Modelling Process approach, built on the work of Busch (1994).

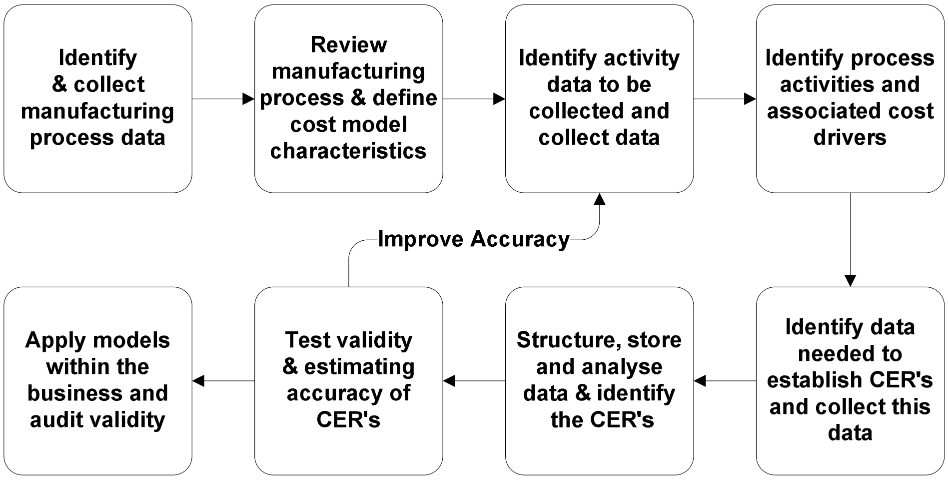


Figure 2.1 Traditional Approach to the CMDP (Adapted from Busch, 1994)

Common features of traditional approaches to Cost Modelling will include the following:

- The CMP is iterative in nature. The tasks of data identification, collection and analysis can take place several times until:
  a. The product and process variables that most affect the cost are identified
  b. The right cost drivers are selected from within these product and process variables
  c. The best estimating relationships have been identified
- The number of times the tasks will repeat will depend on the process or product itself and the cost model characteristics (customer requirements).
- Its iterative nature makes the CMP a time consuming process. The tasks may need to be repeated several times in order to achieve the expected results from the model, i.e. required accuracy, valid relationships among the cost drivers, reproducibility.
- More often than not high levels of process and product expertise are required for the selection of the right process and product data types. Typically, the cost-engineering practitioner will seek information from process and product experts and little to none input from other functions.
- The proper identification of valid cost drivers, and the accuracy and validity of cost models, as a rule, highly depends on the skilled and

professional judgement of the cost model developer and the absence of bias in the process.

- It may also require collecting data at various levels of details, which may not be always available; especially for processes that are in their conceptual design stage.
- The validation of cost models may be difficult because of a lack of process data and cost information, which relates cost drivers to the resource (e.g. process time) or cost (e.g. material cost) the model is built for.
- The absence of the necessary costing data and process information represents a constraint for achieving specific cost model characteristics and increase the lead-time to generate a cost model at the standards expected.

The literature shows that there is no formal scientific research addressing the development of cost models using a formal structured approach. Cost estimating and modelling methodologies focus on the development of cost models for particular applications and manufacturing processes and there is very little published literature on what would represent best/good practice in Manufacturing Cost Modelling Methodology. Only few prescriptive articles on the subject have appeared. The major emphasis is placed on the data analysis tasks and methods employed to establish the CERs (Baguley and Roy, 2007; Shaik et al, 2004 and 2007), rather than on planning and scoping the data identification and collection tasks in the early CMP development stage.

Industrial references to CMD methodologies include in-house organisation or departmental policies, practices and procedures which only refer to documentation required to record assumptions; costing data used; and the analysis methods utilised to develop the CERs/TERs.

Lederer and Prasad (1992) suggest that research on cost estimation has largely focused on the study of algorithmic techniques rather than on the cost estimating process itself. This situation has prevailed for the past 18 years. Model developers describe their own techniques and methods and report their own accuracy assessments. This situation may be biased.

Busch (1994) presents a process (Figure 2.1) where the identification and collection of product and process data precedes the review of the manufacturing operation in question and the definition of the cost model characteristics. The Methodology proposed by this investigation opposes this approach, as the expense of generating a cost model and its output will be a waste if it is not used or does not comply with the requirements.

It is suggested that, if the model's user is to draw valid conclusions from the information provided as output from the cost model, it is necessary to establish the following at the conceptual stage of the modelling process:

- The purpose and business objectives.
- The characteristics and assumptions of the cost model.

The output from the model should be of application to its final user, namely accounting, management, estimating, production, manufacturing, procurement, among some of the business functions the use of the cost model may serve.

Research (Baguley, 2004; Lederer and Prasad 1992, 1993 and 1995; Liyanage and Perera, 2001; Ling, 2005; Salas, 2004; Shaik, 2006) has identified several factors, which are suggested affect the accuracy of estimates and the cost modelling development process in different areas. These factors should, therefore, be considered while developing cost models for estimating costs. Figure 2.2 summarises the factors as found in the literature that affect the CMDP at different levels. There has no evidence of further development in this area since.

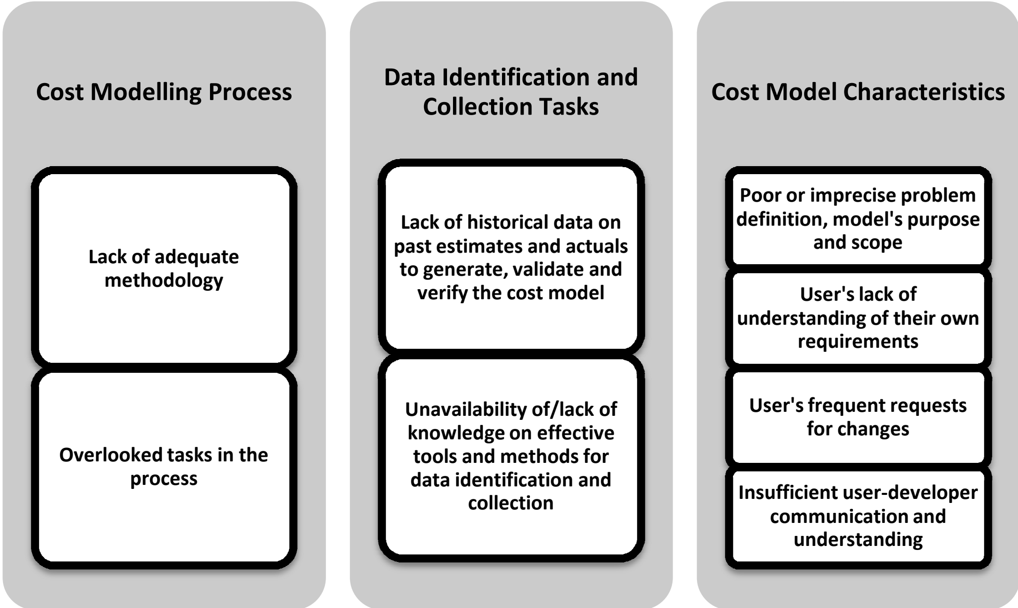


Figure 2.2 Factors affecting the development of Cost Models (Baguley, 2004; Lederer and Prasad 1992, 1993 and 1995; Liyanage and Perera, 2001; Ling, 2005; Salas, 2004; Shaik, 2006).

2.7 Stages in the Cost Model Development Process

Figure 2.3 contains the fundamental stages involved in the development of cost models along with the key tasks in each stage. These are explained in the following sections.

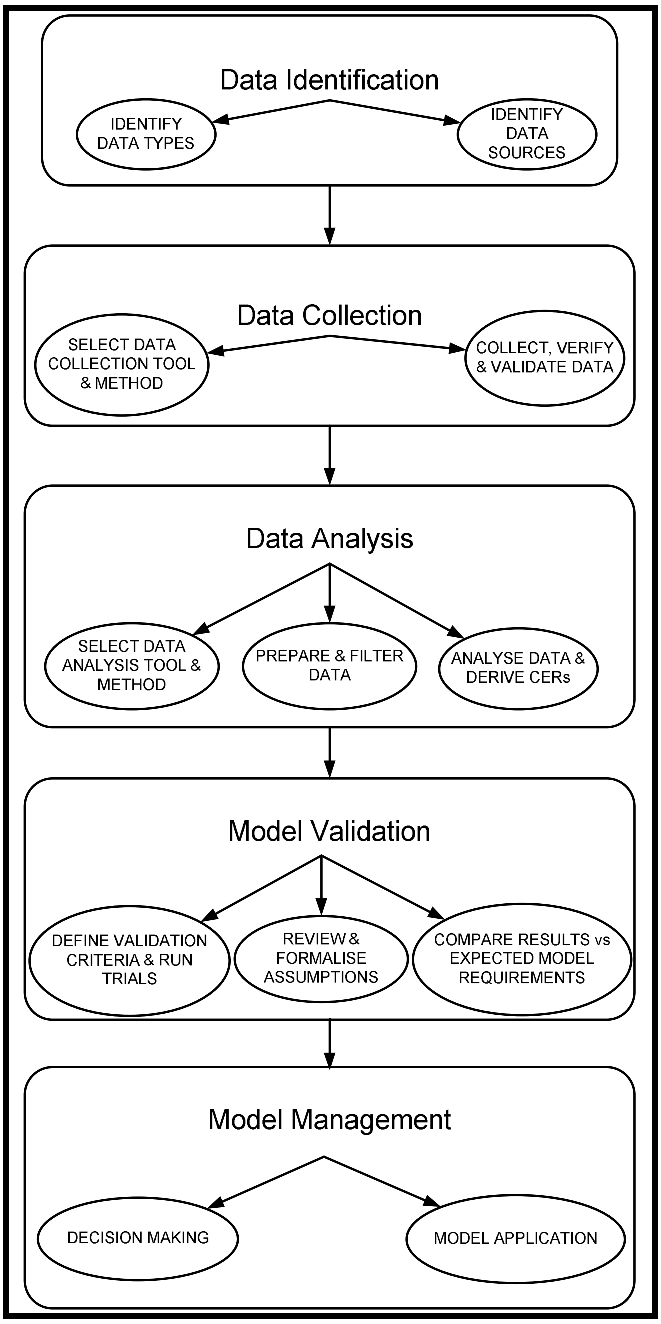


Figure 2.3 Basic stages and tasks in the Cost Modelling Process (Developed Work)

2.7.1 Data Identification

The main objective of this stage is to identify sources of information and data for the elements that most influence the cost of the resource the cost model is built for. This cost elements or data types are predictor (independent) variables that constitute the potential cost drivers. Identifying the right data types or cost drivers is the basis of developing accurate cost models.

Needy et al (1998), ascertains that although many factors could be considered for inclusion in a model, such as total investment, setup, work in process, direct and indirect labour and even energy cost; a model that tries to include all of these factors would be prohibitive and too ambitious both in the ability to collect the data and in the appropriate handling and application of such data in the decision making process.

One consequence of these attempts could be the increment on the margin of error of the model, which may increase with the number of variables or factors included. Another outcome would be higher development times, as the number of iterations around the loop may be expected to increase.

Additionally, the development of accurate cost estimating models is also based on identifying all of the relevant data sources from which those data types can be derived. Moreover, the most suitable data collection TTMs for collating the necessary input data and cost information to build, validate and verify the cost model need as well to be identified. If the number of potential data sources to be examined increases and with it, the number of associated data collection tools, techniques and methods then the total cost of producing the model may also rise.

2.7.2 Data Collection

The aim of this stage is to capture relevant data needed to develop and use a cost model. Issues such as where the data will be obtained from, who is going to collect the data, and when the data will be collected, must be addressed at this stage. Unfortunately, the most frequently recognised shortcoming to cost modelling is the lack of effective data collection and identification tools.

Data collection in the CMP is one of the most important elements in the development of a Cost Model but also a time consuming process. It is affected by the availability of data sources; data types and level of detail; amount of data to be gathered; frequency of data collection; and consistency in the data collection process (Baguley, 2004; Wang, 2000a). These factors contribute to different types of waste throughout the CMP including waiting times, unnecessary motion and effort, processing and rework.

The development of a model is slowed down when the right data is not available in the right format at the right time. Model input data collection takes a long time and is usually the most frustrating and time consuming activity. Model developers have identified a variety of reasons for delays in collecting data. In some cases it is difficult to identify the type of data to be collected. In other situations, after having identified the required data types, a significant amount of time is devoted to collect data.

A considerable research effort has been directed on statistical data analysis but very little on data collection. The analysis of literature has shown that the work by authors such as Dietz (1992), Hatami (1990), Liyanage and Perera (1997, 1998, 2000 and 2001), Lung (1998), Lehtonen and Seppala (1997), Markowitz (1981), Rohrer and Banks (1998), Robinson and Bhatia (1995), and Trybula (1994) has led to the identification of seven major causes of inefficiencies in the data identification and collection tasks, particularly for model input data.

Figure 2.4 highlights the root causes of models lengthy data collection tasks and inaccurate input data and they are explained in more detail in the following sections. This diagram was used as starting point to identify the main areas that required improvement in the cost modelling process and for data analysis as discussed in Chapter 4. An updated diagram is presented and explained in Chapter 5, Figure 5.3.

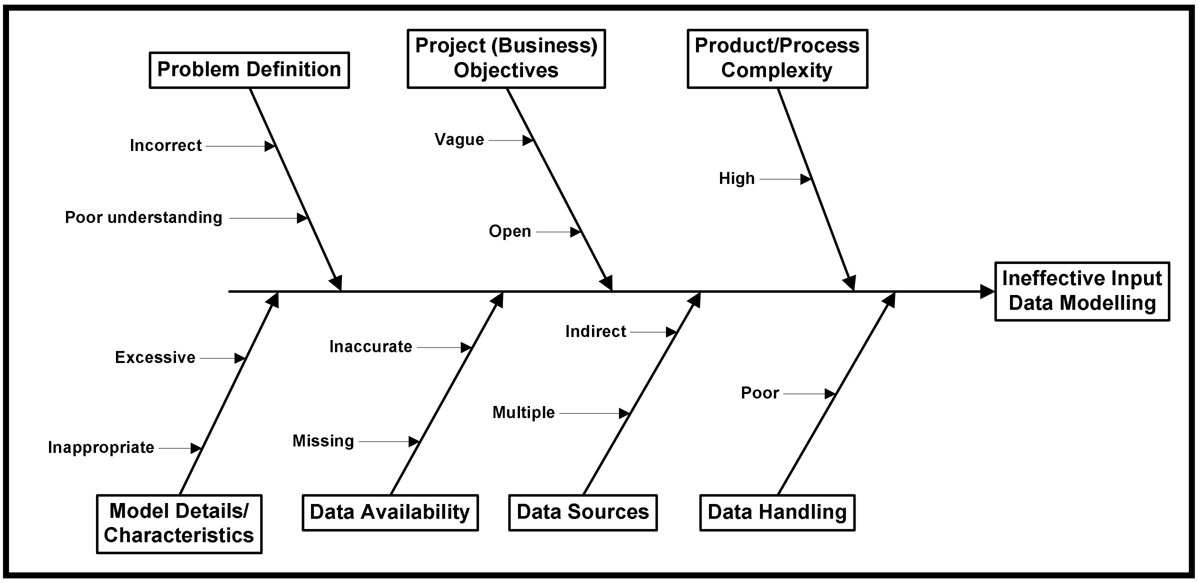


Figure 2.4 Root causes of long data collection tasks and incorrect model input data (Adapted from Liyanage and Perera, 2001)

2.7.2.1 Root Cause - Problem Definition

Before a model is built, a good understanding of the nature and scale of the problem under consideration are required to reduce the risk of failure due to excessive time being invested in gathering inappropriate data (Tye and Perera, 1997) and developing solutions for the wrong problem (Shannon, 1975).

2.7.2.2 Root Cause - Project Business Objectives

Clear project objectives is considered one of the most important, but usually overlooked, parts of a model development exercise (Law, 1990 and 2006; Robinson, 1994). This has a significant detrimental impact on all aspects of the model development process.

Poor definition of business objectives could lead to inappropriate model scope and characteristics (Novel, 1992). This may cause the model developer to identify wrong and unnecessary model data. In addition, a considerable amount of time may be spent on collecting these data.

2.7.2.3 Root Cause - Product or Process Complexity

Liyanage and Perera (2001) reported that in the aerospace and automotive industries, data are often collected in an ad-hoc manner, especially when the process or product under consideration is too complex or large. The authors also noticed that different practitioners adopt different approaches to gather and analyse data even in very similar projects.

The volume and variety of information to be collected is directly driven by the complexity of the process or product under investigation. Depending upon the level of manufacturing activities involved, it may be necessary to gather a large variety of data (Grewal et al, 1995). Tran and Grewal (1997) stated that in any assembly operation, the amount of information to be processed is dependent on the number of tasks rather than the number of parts.

2.7.2.4 Root Cause - Model Details and Characteristics

The level of model detail has clear implications on data collection tasks. It depends on the business objectives; availability of data sources; data types and levels; amount of data to be gathered; frequency of data collection; consistency in the data collection process and the opinion of process experts (Law, 1990). This situation has had little change over the past few decades.

High-level cost models would be expected to exhibit lower level of detail and lower accuracy requirements. Therefore, lower data collection costs associated to them. On the other hand, Low-level cost models, would be expected to deliver high level of detail and accuracy at a higher data collection cost (Figure 2.5).

A higher level of model detail (Low-level cost models) does not necessarily leads to higher model accuracy; instead, it may lead to longer data collection time (Robinson, 1994), effort and cost. The time to collect the necessary information also has an effect on the data collection process and costs (Figure 2.6).

High-level cost models developed during the product/process definition stage of design, also known as Concept models, can be used as the starting point in the development of more detailed models.

A typical data type may have several variables, including some fundamental attributes. These are considered as essential data elements for building the product or process cost model. Collecting data related to core attributes would be expected to be less time consuming and would generally not require much effort. As the model detail increases, more non-core attributes may be brought in. The collection of data for these non-core attributes would be expected to take longer time. Hence, for instance, data collection tasks on process and setup times (core attribute) would require less time and effort than gathering data on machine breakdowns, manning levels or process routes.

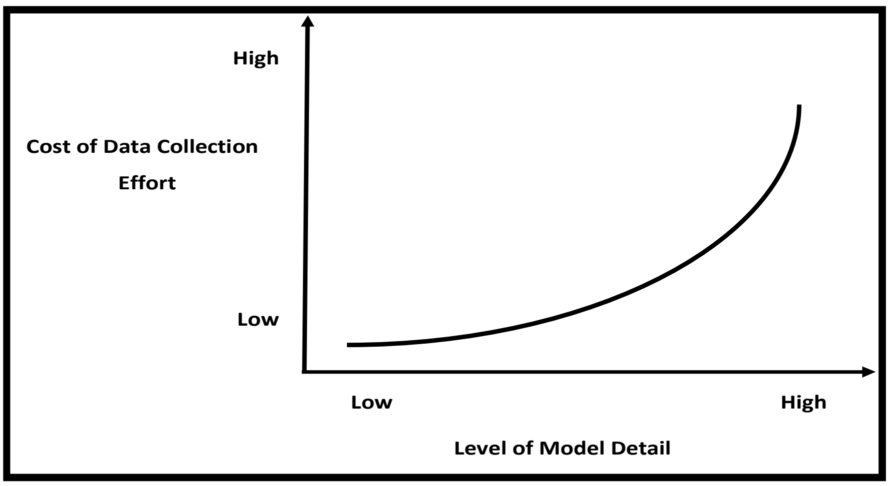


Figure 2.5 Data Collection Costs vs. Level of Model Detail (Developed Work)

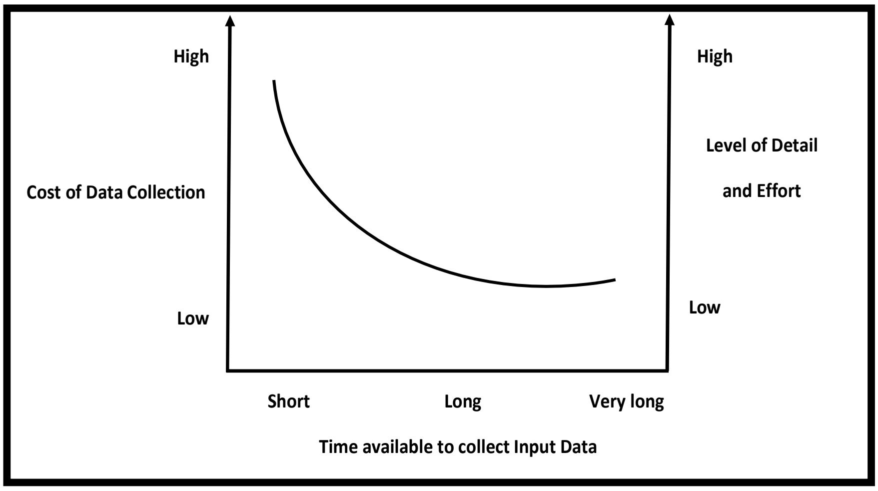


Figure 2.6 Effect of the time available on data collection cost, effort and level of detail (Developed Work)

2.7.2.5 Root Cause - Data Availability

The cost of data collection is driven not only by the project complexity but also by the cost model details and characteristics in terms of the level of accuracy required and, therefore by the level of detail of the input data. But not only that, it will also depend upon the type of data to be collected and its availability, the time available to collect the data and the product or process development stage.

When the model details increased, it may be difficult to find quality data (Hatami, 1990; Robinson, 1994), as the data required may just not be available. Cost models are also developed for process or products still at a definition stage and therefore do not currently exist. In these instances, the model developer may not be able to collect the required data (Figure 2.7), because of unavailability of historical or past information on the process operations, technology or product (Law, 2006; Robinson and Bhatia, 1995).

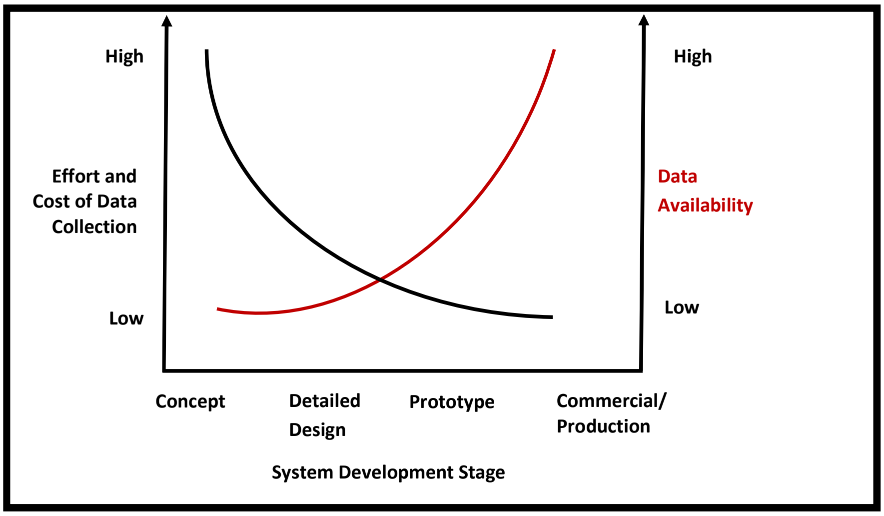


Figure 2.7 Effect of the time available on data collection cost, effort and level of detail (Developed Work)

2.7.2.6 Root Cause - Data Handling

Cost models can be built using customised applications or already available software packages; either way, these systems may not offer facilities to organise and manipulate cost data. Therefore, proprietary data formats are often used.

Manipulating cost data and information to produce the appropriate format for the model may be extremely time consuming. One way to partially address this problem has been via interfacing to spreadsheets and databases. Table 2.4 shows the results from a survey conducted by Liyanage and Perera (2001) on the impact of the factors described above on data collection.

It is evident from the previous discussion that a more structured and methodical approach to data identification and collection is required. According to the information gathered from visits to participant companies and the literature review, apparently there is not a defined methodology or procedure to be followed to collect costing data in an efficient and systematic way. Experience and intuition were identified as the key skills necessary to collect information for building manufacturing cost models. However, the time that takes achieving the right skills is one of the main limitations.

Once the cost model purpose and characteristics have been established, and the data needed has been already identified, building a cost model requires the use of appropriate data collection methods for each particular data source.

RANK	Major Root Causes
1	Poor data availability
2	High level model details
3	Difficulty in identifying available data sources
4	Complexity of the system (process or product) under consideration
5	Lack of clear objectives
6	Manipulation, filtering and structuring input data
7	Incorrect problem definitions (Business Objectives and Model Purpose)

Table 2.4 Impact of the major factors affecting Data Collection (Adapted from Liyanage and Perera, 2001)

Information regarding the level of detail of input data, model accuracy, and cost drivers assists in identifying potential data sources and selecting the most effective data collection tools. These methods must be able to minimise the time and resources required to collect data; while ensuring that the correct data is obtained and that the information is both accurate and valid (Stockton and Wang, 1999).

This investigation aims to develop a CMD Methodology, which will include a Model Scoping Framework to assist cost model developers on the task of data collection by helping them to identify the process and cost model characteristics and so the core data types and then link them to potential data sources. Depending on the availability of data sources, the model builder can be directed to collate the necessary data faster and efficiently by using the appropriate data collection TTMs.

2.7.3 Data Analysis and Development of CERs

There is a wide range of advanced data analysis techniques available for the development of cost models, including Data Mining, Fuzzy Logic and Neural Network. However, the time, cost and accuracy of the model generated at this stage are greatly affected by the predecessor tasks of data identification and data collection. Most of these methods require in-depth expertise and depend heavily on historical data. This situation can be a major constraint as these elements may not be available at all or, in the best case scenario, may be available but not in a reasonable time frame.

One of the most common forms for cost models are Cost (and Time) Estimating Relationships. Cost Estimating Relationships or CERs are mathematical expressions developed by establishing a relationship between one or more parameters, which are observed to change as cost changes (DoD Parametric Cost Estimating Handbook, 1995). These parameters are usually known as cost drivers, as they are highly influential in generating a change in cost or at least, to vary similarly with it.

CERs are typically developed using Linear Regression Analysis. However, other techniques such as Multivariable Regression and Monte Carlo simulation can also be employed.

2.7.4 Model Validation

Model validation (and verification) is part of the CMDP and usually considered to be a process on its own (Sargent, 1994; Ostwald, 1992).

The cost of model validation could be quite significant. A model is considered valid if its accuracy (the one required for the model's intended purpose) lies within its acceptable range. Sargent (2004) ascertains that establishing whether a model is definitely valid over the complete domain of its intended applicability is, in general, too costly and time consuming; in particular, when extremely high level of model confidence is a requirement. This is in part the result of the high level of cost data and process or product information required to perform the cost model validation process.

Often the validation of a model consists of quoting the Coefficient of determination R^2. Other techniques described in the literature include Cross-validation; Graphical and quantitative Analysis of Residuals; Comparison to other models; Face Validity (Expert Judgement); Historical Data Validation; Fixed Values, T-test and F-test. The relationship between the cost of performing model validation and the model value to the user as a function of model confidence is illustrated in Figure 2.8. A similar relationship is held for the amount of time required to perform model validation.

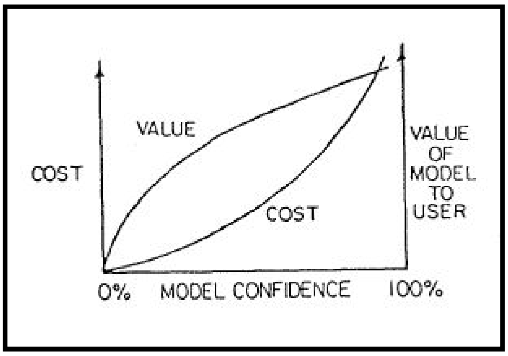


Figure 2.8 Model Validation Cost and Value against Model Confidence (Sargent, 1994)

2.7.5 Model Management

This stage involves the decision-making and model application tasks. The outputs from a cost model should be of use for a number of stakeholders within the organisation. By using the model, the cost engineer or the cost estimator have to provide reliable data relating to the project, product or process under consideration and upon which management might base their decisions. Model Management and Quality Assurance procedures should be in place for the models' storage, maintenance and retrieval in order to ensure that cost models can be made available in an efficient manner throughout the organisation and that they remain up to date.

2.8 Cost Model Characteristics

Cost models exhibit the same general characteristics as any mathematical model. The following sections elaborate on these features and describe, where appropriate, their influence on the data collection process, CMDP and the output of the model.

2.8.1 Cost Model Scope

The first element to be defined before beginning the task of producing a cost model is its purpose. This step will shape the scope and outline the characteristics of the final product. Some authors include this step within their model development exercises without going into detailed explanations or at the most, a basic description of the steps involved.

The model developer should first thoroughly understand the user's needs and requirements before generating the model. An examination of the model purpose requires the consideration of the needs of the various beneficiaries that are the recipients of the model's application. Before initiating the development of a cost model, it is vital to have a clear understanding of these needs and of the cost model requirements as the development process is often time consuming, and frequently requires a high level of resources to achieve a satisfactory outcome.

In addition, potential change requests should be anticipated, reduced and controlled (Lederer and Prasad, 1993). In this context, the importance of methods and tools to accurately identify user's needs and determine model requirements is established.

A model should be developed for a specific purpose (Sargent, 1994) against which its validity should be determined. In other words, the validity of the model needs to be determined with respect to the business objectives and purpose it is intended for. The MSF described in Chapter 6 is an attempt to address this situation. The MSF exercise should take place at the early stage of the CMDP. It aims (among other objectives) to define the function/features of the process or product along with the purpose of the model and to estimate how much data is available, in order to assess the amount of effort required for developing the model and ensure the model will answer the questions involved in the decision making process for the project or product it is built for. Table 2.5, contains a list of basic business objectives and some fundamental purposes that cost models are built to support during the decision-making process at different levels.

A cross-functional approach, which concerns the early involvement and participation of model users and other beneficiaries (such as designers, production managers, manufacturing engineers, among others) contribute to build commitment, and promote open communication channels which may result in timely completion of the cost model and may cause fewer overruns (or underruns), as the model developer's understanding of the user's requirements and changes can be discussed and agreed along the process.

	Decision Levels		
Business Objectives	**Strategic**	**Tactical**	**Operational**
Cost reduction Process time reduction Process evaluation Process improvement Process development Product evaluation Product improvement Product development Standard data generation Capacity planning Production scheduling Pricing and/or quotations Business planning Investment planning Procurement decisions Manufacturing decisions Comparison with other process(es) Bid Analysis Cost/Weight Trade Off Target Cost Should Cost Life/Cost Trade	√	√	√

Table 2.5 Basic Business Objectives and Decision Levels (Stockton et al, 2002)

2.8.2 Detail of Input and Output Data

Meisl (1988) ascertains that one of the main problems in producing reliable cost estimates rest on providing meaningful data for the cost model rather than on building or using a suitable model.

The information that is available to build a cost model depends on the stage of the product lifecycle process the cost estimation is required for. Most researchers stress the fact that cost modelling and estimation must be carried out as early as possible in the design development process (Boothroyd, 1994; Hundal, 1997; Chin and Wang, 1996; Mileham et al, 1993; Wang et al, 2003). However, at the early stages of design, when only the main functions of the design are known, there is very little information to produce accurate cost estimation with. In the literature, the earliest stage at which a cost model was produced was the concept phase (Mileham et al, 1993).

Mileham et al (1993) claims that the only data available at the concept stage is general material type, product general size, form and main features. The authors stress that, although process knowledge is usually not available to the designer at this stage, it is critical for determining the cost. A parametric process specific approach was applied for obtaining the cost estimate and the component weight was used as the primary input.

2.8.3 Model Accuracy and Precision

Cooper and Helfrick (1985) define accuracy as the *"closeness with which […] the true value of the variable being measured"* is approached; i.e., it refers to the degree of conformity to the true value of the variable under measurement. And precision, as *"a measure of the reproducibility of the measurements; i.e., given a fixed value of a variable, precision is a measure of the degree to which successive measurements differ from one another"*. Precision refers to the degree of 'agreement' within a group of measurements.

Accurate cost model outputs at the beginning of a project can provide the required information to decide whether the project is feasible or should be rejected (Shabani and Yekta, 2006). However, at the initial stages of the PDP (preliminary design stages), none to only approximate information and general specifications are available. As design progresses (detailed design stages), more information and process/product detailed data becomes accessible and the accuracy of the model increases.

The costs of data collection and computational data analysis, along with the long development lead times of adding vast amount of detail to a model in pursue of improving accuracy, would effectively inhibit the usage of such a model. Additionally, the uncertainty would increase due to an overly complex system, as each separate part induces some amount of variance into the model. It is therefore usually appropriate to make some approximations, compromising accuracy, to reduce the model to a sensible size. Model users often can accept some approximations in order to get a more robust and simple model.

2.8.4 Level of the Cost Model

The model should provide the necessary information to draw the required conclusions for decision making. It might be required that the information derived from the model goes beyond the simple costing of the product (high level of detail) and penetrates to the cost of the tasks, processes and operations from which the product cost is derived (low level of detail) (Taylor, 1974).

High Level and Low Level cost models may vary depending on the context, industry and expert opinion. In the Aerospace Industry, for instance, a High Level Model can be used to provide cost estimates on a zone or sub-system or for whole airframe or system level. It can be made up from the output of several low level models, from analysis of historical process data, or from amalgamation of Industrial Engineering information. Definition data available for input into the model is limited and thorough understanding of manufacturing processes is not always essential.

A Low Level Model, on the other hand, is used to provide cost estimates usually on a detail component level. This model requires a high degree of component and process information; in addition to in-depth knowledge of the manufacturing process. The development of such models requires analysis of Industrial Engineering information and/or historical manufacturing data.

It has to be pointed out that, although these or similar definitions might be applicable for estimating recurring costs, they might not be suitable for non-recurring costs, such as tooling, for instance.

2.8.5 Model Structure and Consistency

Another important issue in the production of a cost model concerns the consistency of quantitative costing data (used as input for the model) throughout the development process and the consistency of resulting figures obtained as output from a model application exercise. The purpose of consistency is to produce information, results or figures that will be comparable, time after time (Taylor, 1974).

These figures are based on a number of assumptions made and conventions adopted during the development process to meet the terms of user’s pre-established cost model requirements or to comply with internal, industry or international policies, practices or procedures. These assumptions and conventions contained in cost information, i.e.

cost model input or output data, will also depend on the purpose and objectives of the cost modelling exercise.

The scope and potential of cost information can sometimes be underestimated when the figures are merely presented as absolute and irretrievable quantities, when there is no consistency or visibility throughout the process, when there is no clarity in terms of the purpose of the exercise, user's requirements, model characteristics and objectives, its assumptions and conventions. Lack of consistency may result in any of the following:

- Inconsistent outputs between runs of the same cost model.
- Confusing output figures resulting from a model application exercise.
- Inability to conform with the purpose and objectives the model was supposed to meet.
- Failure to comply with the model user's requirements and specification.
- Loss of traceability to detect possible errors, because of poor understanding of the assumptions and/or lack of knowledge on the convention adopted during the development process.

2.8.6 Model Application Time

Models are initially built to comply with the requirements and needs for a cost estimate for a given project, process or product. In today's fast changing and highly competitive market, the lifecycles of some of these processes and products are relatively short, so is the life of the cost model unless it is able to accommodate those fast changes in Technology and Innovation.

2.8.7 Cost Model Responsiveness

A cost model should be flexible and, at the same time, robust enough in order to adapt to changes and incorporate innovation when required. It is also necessary for the model to be 'transparent', as opposite to the 'Black Box' profile that characterised some cost models and estimating approaches.

When the logic, assumptions and rules of the model are visible, then changes can be relatively easy and fast to make, track, explain and, if necessary, to justify. This also adds to improve the level of confidence on the outcomes of the model, as the effect of the modifications and changes applied can be predicted and understood by the model's stakeholders.

2.8.8 Subjective Judgement and Model Complexity

It is well known that complex and dynamic business environments demand the use of subjective information to predict outcomes (Minassian and Jergeas, 2009). Both subjectivity and complexity are considered to be major sources of uncertainty that may lead to not only financial loss but also to total project failure.

Cost practitioners usually use comparison to similar past projects based on personal memory, intuition and guessing as basis of the estimating process. Lederer and Prasad (1992) warn about the customary use of personal memory and related grounds as bases for cost estimating, as they are not associated with greater accuracy. Moreover, the authors suggest that higher accuracy and precision is achieved when there is prevalent reliance on documented facts, established standards, and simple arithmetic formulas for accurate estimates.

Underlying assumptions made during the data collection process and data analysis stage may have large influence on the final cost model and its output. The use of statistical tools assists in diminishing any effect expert judgement may have by identifying and justifying any existing relationship among the model variables.

At the very early stages in the model development process, historical data, experience, and intuitive judgment are essentially the main sources of information used to make decisions. As argued by Minassian and Jergeas (2009), in some cases, when historical data is inadequate or unavailable, the cost modelling practitioners use the subjective judgement of the process or product expert to identify, evaluate and define model variables and subsequently, potential cost drivers. The authors also claim that it is imperative for those who base their decision making process on subjective information to understand or be aware of the degree of risk and uncertainty involved. These two elements, both also subjective in nature, need to be objectively assessed, in order to prevent undesirable outcomes and adverse consequences. There are well-established analytical approaches for Risk Analysis and Uncertainty including Probability Analysis, Monte Carlo technique, Artificial Neural Network, and Fuzzy Set Technique.

Cost Model Uncertainty and Risk Analysis are important not only to predict the expected outcome but also to understand and control the undesirable model outcomes and variances (Neumann, 2002). Early identification, quantification and analysis of model output variance sources provides an opportunity window to set corrective measures early in the model development process; however, this is not part of the scope of this research investigation, as they represent a study subject in their own right (Boehm, 1991). For Meisl (1988), the key demands on cost models include: acceptability to experience and intuition, simplicity and transparency with traceable logic and ground rules, and having an applicable database.

2.8.9 Developers and Users of the Cost Model

The production of cost information is expensive and time consuming (Ferreirinha et al, 1993; Wierda, 1988 and 1990).

Traditional cost information used by the cost estimator may not always suit the designer's needs. The designer will often not have the time to do a cost model or estimate to the same level of detail as the cost estimating practitioner, and therefore a trade-off should be made between the time spent on cost estimation and the level of detail required (Hundal, 1997).

After establishing that the model is suitable for its intended purpose and use, it is necessary to start working on the tasks of data identification and collection at an appropriate level of detail. The data analysis task conducted by the model developer will provide the required CERs.

At this point the user's confidence should be established by any of the following criteria:

- Statistical Validation (R^2, T-test, F-test, among others)
- Output comparison (with those of other models)
- Valid Application to items with known cost
- Expert Judgement Satisfaction

Beltramo (1988) suggests that the model developer and the user should both provide some of these reassurances. However, he states that it is the responsibility of the user to ultimately identify and resolve the issues concerning the model's applicability. In any case, an effective communication between both parts is paramount for the success of the cost modelling process and for producing the expected outcome, namely the cost model.

2.8.10 Set-up and Operating Cost of the Cost Model

The actual cost of a model depends on the cost engineer's skills and the availability and quality of the cost data and information the model is built upon (Park, 1973). The higher the level of accuracy required from the model, the more information on the process parameters, product features, and other design data that is required and the more time required for its preparation.

2.8.11 Performance Measurement Indicators for the Cost Model

Different error measurements are used; however, the most popular error measure is Mean Absolute Relative Error (MARE) (Leung and Fan, 2002). Boehm (1984) suggests the following criteria to be used for evaluating cost estimation models:

- ***Definition*** – Has the model clearly defined the costs it is estimating, and the costs it is excluding?
- ***Fidelity*** – Are the estimates close to the actual costs?
- ***Objectivity*** – Does the model avoid allocating most of the product cost variance to poorly calibrated subjective factors (such as complexity)? Is it difficult to adjust the model to obtain any result the user wants?
- ***Constructiveness*** – Can the model user tell why the model gives the estimates it does? Does it help the user understand the job to be done?

2.9 The Need for a Methodology for Cost Modelling

A cost model is built on information, and the CMDP is, in essence, a transactional process, which greatly depends on human communication. Process and product data and cost information (which the cost model is built upon), represent the unit of work that travels along the different process activities or tasks that the CMDP consists of. It is very difficult to assign a value to a unit of work in the CMDP and to quantify the effect of missing information at each stage of the process. Other limitations include:

- It is difficult to define a defect; however, the feeling is that the effect might be very high
- Mixture of data types (discrete and continuous; process features, product features, process activities)
- The financial impact and benefits of the cost model are difficult to quantify

- Costing data comes from a variety of different information systems and sources
- Historical data may be available, however, it is filled with errors
- Work in progress is not visible and its financial impact is unclear
- Cycle time data and performance metrics are unclear and not recorded
- Huge amount of time is spent dealing with recurring issues (identifying and collecting data, re-visiting the data source)

The scope and potential of cost information is sometimes underestimated when the figures are only presented as absolute and immutable quantities, when there is no consistency throughout the process, when there is no clarity in terms of the purpose of the exercise, its assumptions and conventions. Data used in the development of cost models and estimates traditionally comes from a variety of sources (Hollmann, 2006b; Park, 1973; Rush and Roy, 2001a; Winchell, 1989). Timely and reliable data sources are paramount for reducing the development time of cost models, and contribute to make the CMP more effective and 'leaner' by eliminating process waste (waiting times, over-processing, among others). In addition, data sources add value to the final product of the CMDP, as the accuracy and validity of cost models depend largely on their data sources.

Along all disciplines the accuracy of the cost models and ultimate estimates is a critical factor and the effect of the data availability and reliability continues to be a challenge. Improvements have been made and some disciplines have made an effort to develop best practice methodologies. Examples of these are the AACEI Total Cost Management (TCM) Framework (AACE International, 2006) and the United States Government Accountability Office (GAO) Cost Assessment Guide (2007).

The former document, the Total Cost Management (TCM) Framework, is defined as *"a systematic approach to managing cost throughout the life cycle of any enterprise, program, facility, project, product or service [...] that provides a structured, integrated overview of cost engineering."* (AACE International, 2006:ix). This is a generic guideline or reference process model that applies to all industries. It is to be used by all levels of practitioners and worldwide in all environments including industry, academia, institutions and Government. It is relevant to the entire lifecycle of assets and projects.

The application of cost models is mentioned in Asset Planning. They are tools widely used when the *"level of scope definition increases"* (AACE International, 2006:50).

Asset life cycle cost models used for Asset Planning can also be used to support investment decision making for project execution. The models are useful for risk and assumption monitoring through project execution.

Cost Estimating and Budgeting is discussed in Chapter 7 of the TCM Framework where the applicability of cost models is mentioned once again. This time they are referred to as suitable tools for simulation and optimisation purposes. Cost models, therefore are described as the means rather that the end product. They are enablers within the Cost Estimating Planning sub-process of the Strategic Asset Management Process (with a stochastic approach) and the Project Control Process (with a deterministic approach) sections of the TCM Framework.

More than thirty years ago, the U.S. Government Accountability Office (GAO) reported that realistic cost estimating was imperative to decisions making for acquiring new weapon systems (Comptroller General of the United States cited in GAO Cost Assessment Guide, 2007). They stated that cost estimates to develop and produce weapon systems were understated. They identified factors in the cost estimating function that were causing this problem, including the following:

- Lack of uniform guidance on cost estimating practices and procedures within the DoD, with each service issuing its own guidance for creating cost estimates, which ranged from a detailed estimating manual to a few general statements. In addition, cost estimators often ignored those guidelines.
- Historical cost data used as a basis for computing cost estimates were at times invalid, unreliable, or unrepresentative. In addition, readily retrievable cost data were generally lacking.
- Lack of structured and systematic effort to collect actual cost information to achieve comparability between data collected on various systems or to make any effort to see whether the cost data the contractors reported were accurate and consistent
- Lack of realism and objectivity in the cost estimating process, leading to biased and over optimistic cost estimates of weapon systems

Unfortunately, this situation occurs in a variety of industries and domains worldwide; it is not exclusive to the US DoD. Furthermore, case studies drawn from GAO’s reports (GAO Cost Assessment Guide, 2007) show that despite having in place a list of basic characteristics for (credible) cost estimates which have been studied, published and highlighted in numerous occasions, many government agencies still lack the ability to develop cost estimates that can satisfy these basic characteristics.

The GAO Cost Assessment Guide is an attempt to correct this situation. The guide provides a cost estimating methodology based upon two general estimating exercises: a Bottom Up cost estimate component which uses the Work Breakdown Structure (WBS) approach and a Top Down risk analysis component which includes qualitative and quantitative risk analysis exercises. It consists of best practice processes, standards, and procedures for developing, implementing and evaluating cost estimates. In combination, they represent an overall twelve-step process of repeatable methods. The GAO's Cost Estimating Process is shown in Figure 2.9.

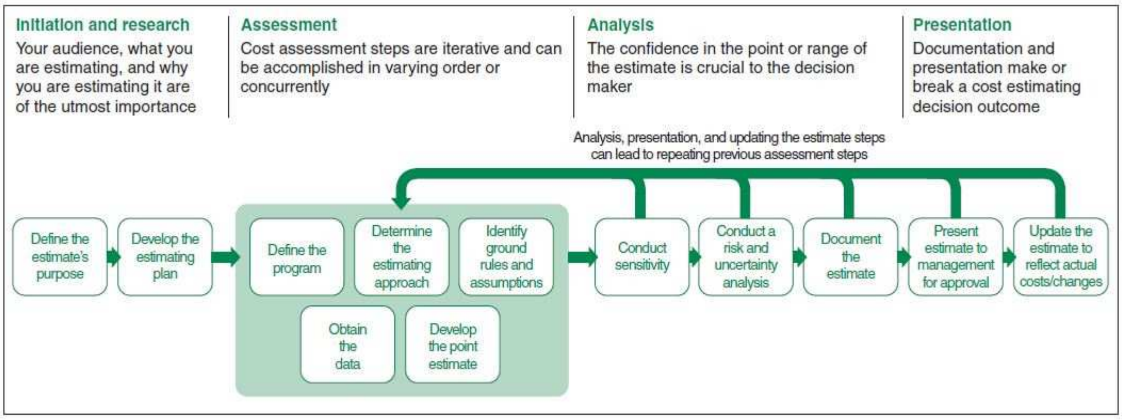


Figure 2.9 GAO's Cost Estimating Process (GAO Cost Assessment Guide, 2007)

The methodology recognises that one of the most time consuming steps in the cost estimating process is obtaining the data (Step 6 in Figure 2.9). It states that enough time should be scheduled to collect the data, including visiting suppliers' sites to further understand the strengths and limitations of the data that have been collected. Furthermore, schedule constraints should be clearly identified in the ground rules and assumptions if there is not enough time to develop the estimate, so that estimates' final users understand the effect of the constraints on the quality and confidence of the estimate. It highlights other cost estimating requirements such as good organisational skills, in order to pull together different data for each cost element and to present it in a meaningful way. It also mentions engineering and mathematical skills, to fully understand the quality of the data available.

Communication skills are also considered important for clarifying the technical aspects of the project with technical specialists and to interact with experts in a meaningful and productive way. On the other hand, if the project has no technical baseline description, or if the cost estimating team must develop one, it is vital that the estimators have access to the subject matter experts (project managers, engineers and analyst) familiar with the actual or similar project.

The GAO's Guide recognises the difficulties associated with data collection and identifies ten data sources for Weapon Acquisition programmes, categorising them into primary and secondary data sources. It provides a comprehensive description on the data sources' applicability, types, limitations and handling and management tasks, but only elaborates on the requirements from the data collection methods. It establishes that data can be collected using interviews, surveys, data collection instruments and focus groups but does not elaborates on the methods or procedures and on what data (types or sources) they are applicable to. The GAO's estimating process includes a Data Collection Instrument. This document is divided in two parts; the first part is basically a data request proforma asking for copies of a series of listed documents and reports; the second part includes open questions on contract, program management and cost and earned value management systems. There is a data request rationale that accompanies the Data Collection Instrument.

Despite being considered best practice and offering a comprehensive approach to cost estimating, this methodology and other traditional CMD approaches (including NASA's 2002 Cost Estimating Handbook and DoE's 2004 Cost Estimating Guide) lack a structured procedure or method for defining the characteristics of the cost model (not the final estimate) that need to be developed; namely, the model's estimating accuracy, level of detail of input data, manning levels, and the level of experience and time required to build the model, under which conditions a data source or data collection tool is more suitable to collect the required information, just to mention a few.

Consequently, there is a lack of performance metrics and their associated target values (benchmarks) that could be used to ensure a 'fit for purpose' cost model. These targets are also necessary to provide guidance for determining an end point to the cost model development process itself. Perhaps, the closest documented generally-accepted guidelines are the AACEI recommended practices No. 18R-97 (AACE International

Recommended Practice No. 18R-97, 2005) and No. 17R-97 (AACE International Recommended Practice No. 17R-97, 1997) on Cost Estimate Classification Systems.

These guidelines are based upon cost engineering practices used in a broad range of process companies worldwide, as well as published references and company and public standards. The documents provide guidelines on general principles of estimate classification for project cost estimates; that is cost estimates that are used to evaluate, approve, and fund projects for engineering, procurement, and construction (EPC) work for the process industries.

They do not cover cost estimates for the products manufactured by the process facilities, or for research and development work in support of the process industries. Furthermore, it does not cover cost estimate classification in non-process industries including transport, manufacturing, software development and similar industries. It also does not explicitly address estimates for the exploration, production, or transportation of mining or hydrocarbon materials, although it may be appropriate to some of the intermediate processing steps in these systems. Despite all of the above, they are still referred to as a starting point.

The RP No. 17R-97 is a more generic recommended practice that can be applied across a wide variety of industries. Although they are developed as guidelines for estimate classification, given that cost models are instruments used to generate the cost estimate, these practices are still used as reference guidelines for the purpose of defining the scope of cost models based on the expected outcome; that is the cost estimate, which is not necessarily considered by the researcher as best practice.

In addition, prior to the model building process, methods for specifying products and processes a cost model is required for, other than experience and judgement of cost engineers and process experts, are also scarce. This information is key for determining the potential data types, and the data sources that will be available during the CMP data collection tasks. Identifying data sources at this stage is critical in order to make available to cost engineers and model developers with knowledge of potential conflicts between the cost model characteristics required and the ability of available data sources to enable such characteristics to be achieved.

The proposed CMD Methodology aims to provide both a structured methodology for cost model development and detailed information concerning the decisions and assumptions made by the cost model developer. Structure and transparency of decision making provide the basis for the use of accepted quality assurance and model management systems, such as British Standard BS 6001-0:2006, to ensure that the validity of cost models can be continually updated.

2.9.1 Waste in the CMDP

In the CMDP, waste can be identified in the form of:

- Number of times going through the process loop
- Unnecessary or limited data/expertise available
- Non-value added activities
- Time consuming and unresponsive to users' needs, long development lead times
- Lack of coherent and consistent approaches
- Relying on process and product experts input to generate cost models
- Inaccurate estimates (major number of predictors required, higher level of complexity, shorter development cycle times).

One way of making the CMP more responsive will consist of, initially, improving the process visibility and data traceability. The strategy must include identifying and mapping the process tasks and eliminate the non-value added activities.

The next step will consist of standardising the CMDP. To this end, it is required to define the Cost Model Characteristics by listening to and identifying model users' needs and identifying model requirements according to the Business Objectives and Model function. The next step is to follow a well-defined, structured and standardised methodology.

The work conducted to achieve these objectives is explained in the following section and developed further in the following chapters.

CHAPTER 3. THE USE OF COST DATA AND INFORMATION IN THE CMDP

3.1 Introduction

As pointed out by Cheung et al (2009), having available good quality historical data and knowledge to support the cost estimation process will allow faster responses to the designer. Timely and reliable data sources play an important part on minimising the development time of cost models, and contribute to make the CMP more effective. In addition, the accuracy and validity of cost models depend to a great extent on their data sources, thus adding value.

In order to understand what methods or tools are the most appropriate for collecting costing data, it is necessary to define at front the type of data that is ought to be collected. Early developed work as part of this research presented a Taxonomy for manufacturing cost data elements or product features, process features and process activities at three well defined levels of detail. The current investigation builds on this classification, develops it further and validates it using a modified version of the Path Diagramming Technique.

This chapter also describes the identified sources of data cost engineers employ to gather information for building, verifying and validating the cost model in a variety of contexts and industries. In addition, existing and potential data collection tools which may be used to extract the required information from them are also described. Taxonomy for data sources and data collection tools, techniques and methods (DC-TTMs) is proposed.

3.2 Sources of Information for the Development of Cost Models

The cost information to be collected consists of the actual input data for the model and the necessary data to verify and validate the model itself. Costing data include economic parameters (wages, working days per year); design specifications (part dimensions, materials) and production parameters (production rate, scrap rate, cycle time, set up times). As listed on Table 3.1, data used in the development of cost models and estimates traditionally comes from a variety of sources (Hollmann, 2006b; Liyanage and Perera, 1998; Park, 1973; Rush and Roy, 2001a; Winchell, 1989).

Data sources could be also described according to the way the data is collected as primary and secondary data sources (Chakravarti et al, 1967). Primary data sources are those from which the data is collected directly by the immediate user. In contrast, secondary data sources refer to those sources where the data have been collected by a subject or organisation other than the immediate user of the data.

Type of Information	Examples/Sources
Combination of common sense, logic, skills, experience and judgment	Information obtained from the expert knowledge of cost engineering practitioners, such as cost estimators, cost engineers, value engineers, project managers, and parametric analysts.
Model purpose and characteristics	Information supplied by the model user.
Historical cost information	Information acquired from previous costing estimating exercises generated for the same or similar projects, processes or products.
Manufacturing, design, procurement, and sales data	Information provided by the project or process owner, and members of the project team.
Internal and external information	Information obtained from customers and suppliers of the project or process.
Other sources of information	Published literature, proposals, databases, Institutions and Associations, and Government Departments.

Table 3.1 Common Sources of Information in Cost Modelling (Developed Work)

In many situations, the need for relevant information can be met by gathering useful data from secondary sources; this is compiling data from information already collected by international or governmental agencies, research institutions, commercial organisations, suppliers and distributors, shop floor operators, product and process experts, among others. Frequently, however, the cost practitioner may find that the required data is not readily available and that they have to be collected first hand from primary sources, particularly for those processes or products at the earlier stages of development.

Developed work by the author identified common data sources, but also new sources of information, which appear to be gaining popularity in the past few decades. The World Wide Web, for instance, has made available a variety of online resources including electronic databases, specialist web sites, Professional Institutions, public bodies and the Government, patents and standards, special interest and discussion groups, electronic mailing. In the CMP, extensive and complex research might take time and require specialist knowledge to reach the expected outcome. All these online sources allow having fast access to vast amount of information; and consequently, add value to the CMP as they simplify the data identification and collection tasks; promote using less effort by eliminating motion; and combine or simplify tasks in the process.

The applicability of data sources on the generation of cost models will depend not only on the characteristics of the data source itself (Hollmann, 2006b), but also on the purpose and characteristics of the model and those of the process or product a cost model or estimate is required for. According to the literature review and later confirmed by the survey results, data availability seems to be the main driver for the level of detail a cost model can be built at and the defining factor for the cost model characteristics, rather than those elements such as user requirements, model purpose and the business objectives the model aims to serve.

In the CMP, once the appropriate data sources have been identified, then the data collection tasks take place. Their function is to capture data relevant to the resource a cost model is required for. At this stage, issues such as time available to collect the data, what data will be collected, resources, among others must be addressed (Shaik, 2006).

Traditionally, the basic cost elements or resources of costs are labour, materials and overheads. Some sources of information in the Built Environment, Civil Engineering and Construction industry consist of cost publishers, architecture-design reference books, land developers and planners' guides, which publish high level parametric cost information for site development.

Cost data can be historical. Accounting reports are historical in the sense that they are transactions recorded through cost-controlling accounts kept in a ledger system. Some cost data are measured. Work measurement methods give information that is amenable to estimation, either in time or currency (dollar/pound value) dimensions. Material quantities can be calculated from drawings and specifications.

Cost data can be derived from predetermined policies. Policy data, as defined by Ostwald (1992) have the property of being fixed, accepted as factual and often unchallengeable for engineering purposes. Policy data on wages and salary, and types of labour on equipment to be operated, budgets and governmental restrictions come from internal departments within organisations, official government sources, international agencies, trade associations, trade unions, sampling organisations, or any office that gathers and divulges product, design, market and economic information.

Accounting, personnel, and operating departments are also sources of cost information in the construction and manufacturing industry. Supervisors and operation managers are direct sources for information on costs of process equipment, manning, efficiency, scrap, repairs and down time, as for their familiarity with the process or operation involved. Purchasing and departments can be frequent sources of cost information. Information on pricing of products, such as market demand, sales, consumer analysis, brand loyalty, advertising and market testing can be obtained from sales and marketing departments.

Information on basic economic facts and trends is available from the American Government and related organisations; elements of cost on material and labour can be obtained from the Bureau of Labour Statistics. In the UK, information can be obtained from the Chamber of Commerce, Office for National Statistics (ONS), and the Confederation of British Industry (CBI). Information on Legislation (if applicable) can be obtained from Office of Public Sector Information (OPSI).

Cost estimation has always been part of any manufacturing venture (Wei and Egbelu, 2000). In the manufacturing industry, engineering cost data is sometimes published by Trade associations subsidised by business groups sharing a common need (such as AACEI, IET, ACOSTE, and IMechE). Data sources also include MRP II and process planning systems, maintenance and quality control records, production process sheets, Computer Aided Design (CAD) systems among others.

In the early stages of a product design, when data is scarce, basic parametric cost estimating relationships, such as weight-based relationships may be used. As the design is further developed and more detail is added onto it, more information is made available and cost estimates can be developed based on design features, manufacturing features or even a process plan (activities). New cost estimating relationships will be utilised instead of the earlier parametric relationships. Additional features, including estimate error scaling and trade study capability can also be included.

3.3 Costing Data and Level of Information

Cost data are collected in several different ways and from a variety of sources. These sources can vary from simple manual systems to sophisticated computer based systems. Even so, cost model developers may find difficulties when collecting the required data and cost information due to the existence of different data sources for the same data type. Furthermore, because of lack of integration between systems, two sources may provide different values or formats for the same type of data. Because of these uncertainties, the cost model developer may ask for a third party opinion in order to identify a more accurate data source.

In the same way, sometimes the required cost information may not be directly available in the required format but as in a very crude data form; hence significant time and effort may be needed to collect, filter, organise and analyse the data.

According to Wang et al (2000b) the input data required to develop and apply cost models can be grouped into three basic areas:

- Economic parameters: wages, working days per year, which can be determined by the plant location and related environmental factors.
- Design specifications: part dimensions, materials, driven by the product design.
- Production parameters: cycle times, scrap rate, units per year.

A study by Busby (1997) on the nature of feedback in engineering design organisations found that the delay between the design decision and the determination of the associated cost negatively influenced the designer's ability to learn about the process consequences of design decisions. Furthermore, the repercussions of the decisions that impacted the cost were often not fed back to designers at all despite the importance of the design details to product cost.

Decisions such as the selection of a particular material can easily be seen to influence the product cost. However, decisions like a radius, tolerances or blend composition may result in the need for a tool change, new setup or even a processing machine change, which will be adding to the manufacturing cost of a part. Therefore, producibility is more often than not included in the estimation of the cost of producing a part or component. In spite of this, functional specifications usually drive the design process.

A secondary goal of this research investigation is the implementation of a library database of product and process dependent cost factors to enable cost engineers and practitioners to identify predictor variables (cost drivers) and their associated data sources, as well as the most appropriate data collection methods.

The literature review for this subject shows the heterogeneity in sources for data elements that go into the development of cost models. Although this investigation does not provide a rigorous decomposition into specific data elements by data source, it provides an overview of the general data types that can be obtained by using particular data sources and the potential Data Collection Tools, Techniques and Methods (DC-

TTMs) which could be employed for cost data and information gathering. Data sources identified in the study were grouped into categories according to their nature, main features and their application within the CMP.

3.3.1 Data Classification

There are different criteria to categorise input data. For the purpose of this study input data for cost modelling will be grouped according to three basic principles: functionality or basic characteristics (Categories); function (Data Types) and Level of detail (Data Level).

3.3.1.1 By Categories

Process Sources

Process sources relate to the manufacturing process involved in the production of the product to be costed. The process examined could be the culmination of several smaller processes that could be either separated or viewed as a whole entity when developing the model. These include:

- Actual Process
- Video of Process
- Process Expert
- Similar Processes
- Process Controllers

Synthetic Sources

Synthetic data sources are generated from historical time studies of operational data, labour times and material costs (Mundel, 1978). They cover ranges of situations and for this reason can be inaccurate when the product or process to be costed is detailed in definition. However, when an operation is required many times within the overall process, the usefulness of synthetic sources as a mean to identify cost drivers becomes apparent. They are also useful in aiding the cost engineer to apply their knowledge to the baseline estimate and weight accordingly to their expertise using scaling factors. These include:

- Synthetic Standards

- Standard Predetermined Motion Time Systems (PMTS) Systems, including Maynard Operational Sequence Technique (MOST), Methods Time Measurement (MTM) and MODAPTS PLUS.

Product Sources

All sources that are particular to the actual component are under this category with a particular emphasis on the features of the product, tolerances of the features, frequency of features and materials of fabrication. These include:

- Costed Components
- CNC Programmes
- CAD Files
- Product Specification
- Engineering Drawings.

Equipment Sources

This source type is based around the process equipment and how it is utilised, operated, maintained, outlying operating parameter and performance parameters. This is the domain of operator of machinery and miscellaneous personnel involved in the process. These include:

- Equipment Specification
- Maintenance Manuals
- Operating Manuals
- Training Manuals
- Equipment performance

Model Based Sources

By the creation of models data can be generated and analysed to identify the process time drivers, product feature cost drivers, material cost drivers and indirect process time drivers. These include:

- Process Models
- Empirical Laws (Statistical models are included in this category)
- Physical Models

Internet and Paper Based Sources

With the evolving computer based technologies allowing easy access to company knowledge and information their use as a data source for model development is essential. Many of the sources of data could still be hard copies on paper though their location could be held on a computer data or knowledge management system allowing tracking of this knowledge enterprise wide. These include:

- Literature reviews
- Departmental records
- Operator's Black Book
- Quality manuals and reports
- Planning and Control Sheets
- Shopfloor Documentation
- Patents
- Internet

Heuristic Sources

A *heuristic* is a list of general rules containing engineering knowledge and experience that can be followed, or used to identify data within a particular stage of a process. Heuristic methods have been used for detail manufacturability evaluation and analysis in a variety of manufacturing domains (Zhao and Shah, 2005).

In manufacturing, heuristic rules are used to identify infeasible design attributes that may cause manufacturability problems. This sort of rules may include general guidelines that are independent of the domain as well as process specific. They should contain lessons, knowledge and experiences of engineers to be of use in engineering practice. However, they are difficult to collect and generalise.

Examples of general guidelines may include maximising the use of standard components, tools, and materials and minimising part count and geometry complexity. A list of heuristics can be included within a flow diagram or process map as a formal guide or rule to identify process features. The rate of change indices for a collection of features, for example, can be ordered by engineering experience and captured within a set of heuristics. Tosun et al (2009) use two feature weight assignment heuristics to rank project features by modifying the standard statistical process of Principal Component Analysis (PCA). These sources include:

- ***Expert Opinion*** - it is used significantly during the generation of cost models and estimates (Rush and Roy, 2001b) to make assumptions and judgements about the cost of a new product, or costs associated to a new manufacturing process or new technology. No matter the cost model approach or the tools used to build the cost models, once calibrated, judgement and expert opinion is needed to review the validity of calibration data, and during the input of parameter values. It is the cost estimator and their expertise that ultimately controls the output of any cost model. The specialised knowledge on the process and product may be acquired by experience, education, observation, or study.
- ***Rules of thumb*** – they can be built up from a literature search and formal gathering of expert opinion. Existing methods and expert systems already use heuristics within certain costing applications (Madachy, 1997). Performance measures and metrics can be used if required as a more sophisticated form of heuristics. These heuristics are considered more akin to data collection methods.
- ***Creative thinking*** - it can be defined as the process of "shaping associative elements into new combinations which either meet specified requirements or are in some way useful. The more mutually remote the elements of the new combination are the more creative the process or solution" (Mednick, 1962: p 221). This methodology for product design has been discussed in the literature. The same process may be of use when approaching situations where data and information may not be readily available; hidden or non-documented (informal) procedures and rules may be applied to fill in the gaps and make the required assumptions until more information becomes available.

3.3.1.2 By Types (Process Cost Elements)

Cost models can have the form of equations or statistical relationships between cost or time and physical or performance characteristics of past designs such as process parameters and design variables. Sometimes those characteristics or parameters are called cost drivers (Ogunlana, 1989). Identifying the right data types or cost drivers, early in the development process, is the first step in the generation of accurate estimating models (Hicks et al, 2002). They are essential for the selection of the most appropriate data sources. In the same way, data types assist to identify the most effective data collection methods to be used during the data collection stage (Stockton et al, 2002).

During the data identification tasks that occur at several stages during the overall CMP, it is essential to identify the basic data types or data cost elements to be gathered at the data collection stage, as they are the potential independent (predictor) variables of the cost and time estimating relationships or cost drivers. Three basic data types or process cost elements (Table 3.2) have been identified and categorised (Stockton et al, 2002).

	Level of detail		
Data Types	**Level 1**	**Level 2**	**Level 3**
Product Features	Product	Component	Component feature
Process Features	Machine	Machine Assembly	Machine Sub-assembly
Process Activities	Process	Process Operation	Operational Activity

Table 3.2 Data Types and Levels of Detail (Stockton et al, 2002).

Measures of technical capability, such as thrust, weight and specific fuel consumption for an aircraft engine are design variables that would fall into the Product Feature category. They can even be further divided into cost drivers that are scale dependent and independent. For instance, weight and trust will generally increase as the engine becomes larger; therefore, these parameters are scale dependent. Other performance parameters such as the rotor inlet temperature and bypass ratio do not necessarily scale with size; hence, these are scale independent.

Manufacturing cost models are often built using parametric relationships to establish CER (Cost Estimating Relationship) of the form:

$y = a + bX_1^n + cX_2^m + ...$ (equation 1)

where:

y is the dependent cost element

X_1 is the 1st predictor element

X_2 is the 2nd predictor element

a is a constant

b is the coefficient of the 1st predictor

c is the coefficient of the 2nd predictor

a, b, c, n, and m are parameters to be found and dependent of the model and process characteristics.

In traditional manufacturing cost estimating, input cost data elements consists of potential process sequences, processing times, hourly rate (for labour or machining) and other miscellaneous cost data. In other words, cost elements are process activities, process features or product features at any of the three levels of detail (Table 3.3).

In order to define a CER for any resource (Figure 3.1) the dependent variable or cost element is defined by a combination of variables falling into any of the three cost data types (Table 3.4). It would be expected all cost elements to be at the same level of detail.

The estimating process then breaks down the costs involved into a series of simple calculations done manually or more commonly on a computer using specialised estimating software. It is important that, at the model's concept stage, the cost resources are effectively established. In the same way, because this step shapes the beginning of the CMDP for the product or process selected, it is necessary to be quite specific in terms of the level and type of the cost elements that the cost model users or beneficiaries want it to be developed for (Stockton et al, 2002).

	Level		
	Level 1	Level 2	Level 3
Process Elements	**Product**	**Component**	**Component feature**
Product Features	At a product level, these are features that correspond to an entire product or a complete assembly of a multitude of components as in the case of a complete airframe or engine.	At a component level, these are individual parts or components which make up the product, including for instance, L/D radio, material, faced surface, turned surface, for a milling operation	It refers to individual attributes of a component feature. It is very detailed information, which could also, include feature tolerances. For example, thread, chamfer, number of holes.
	Machine	**Machine Assembly**	**Machine Sub-assembly**
Process Features	It relates to higher level attribute(s) of the machine or piece of equipment involved in the manufacturing of the product under consideration. For example, turning speed, feed speed, type of cutting tool, number of axes, horsepower for a CNC Machine Centre.	Machine assembly level involves each section or unit of the machine/equipment according to their particular functions. Electrical system, material handling device, tool changer, tool locator for a CNC machine centre are some examples.	A process feature at the sub-assembly level would be each individual feature, which form part of a particular unit or section of the machine or equipment involved, such as the tool holder in the machine's tool changer unit.
	Process	**Process Operation**	**Operational Activity**
Process Activities	This level corresponds to the higher level of information of the main process tasks involved in the manufacturing of a product, as for example loading and unloading the piece, machining, inspection, set-up	A process activity at the process operation level is each of the individual operations involved in the execution of a main task such as boring, grinding and turning operations.	At an operational activity level, a process activity is described as each work element performed by a machine tool or equipment, or by an operator. For a manual operation, work elements will be in the form of body movements (or basic motions). For a machining operation, they will be individual movements of a tool. It will include individual movements of a tool changer: depth of bore etc. Operator moves for grasping, positioning, holding.

Table 3.3 Outline of Process Cost Elements (Data Types) and their Levels (adapted from Stockton et al, 2002)

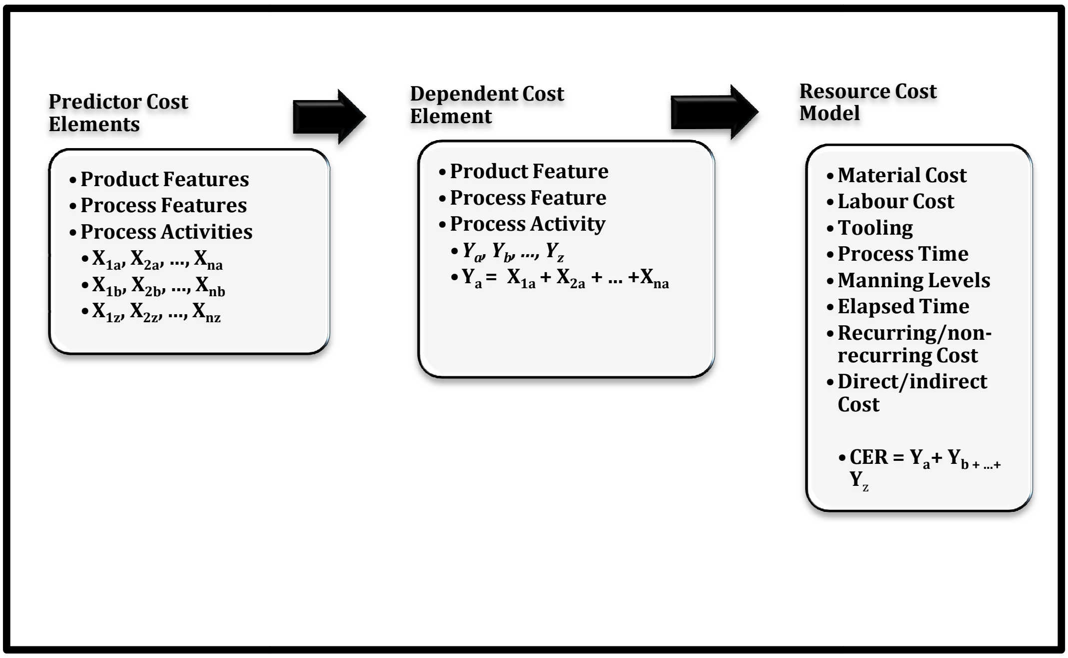


Figure 3.1 General Representation of a Manufacturing Cost Model (Developed Work)

	Common Cost Resources to be estimated							
	Material		Labour		Equipment		Process Time	
Level of cost data required	Direct	Indirect	Direct	Indirect	Recurring	Non-recurring	Direct	Indirect
Product Features								
Level 1: Product Level	√	√	√	√	√	√	√	√
Level 2: Component Level	√	√	√	√	√	√	√	√
Level 3: Component feature level	√	√	√	√	√	√	√	√
Process Features								
Level 1: Machine Level	√	√	√	√	√	√	√	√
Level 2: Machine Assembly Level	√	√	√	√	√	√	√	√
Level 3: Machine Sub-assembly level	√	√	√	√	√	√	√	√
Process Activities								
Level 1: Process Level	√	√	√	√	√	√	√	√
Level 2: Process Operation Level	√	√	√	√	√	√	√	√
Level 3: Operational Activity Level	√	√	√	√	√	√	√	√

Table 3.4 Common Cost Resources to be estimated and Level of Cost Data Elements required. (Developed Work)

The path diagram in Figure 3.2 shows a schematic representation of the resources, cost element types and levels described above. The path diagram is used in the new CMD Methodology as a visual tool to present the results from the Pair Comparison exercises (Chapter 6).

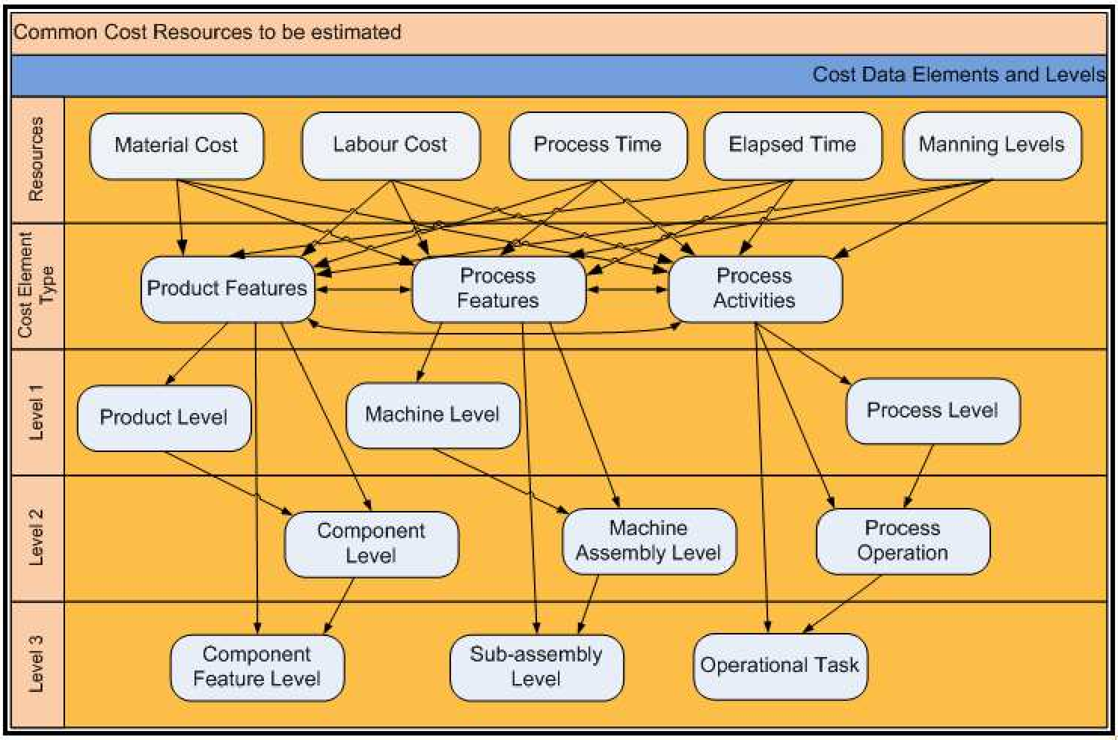


Figure 3.2 Path Diagram for the different Cost Data Elements (Developed Work)

Figure 3.3 is an example of the breakdown of Direct Material Cost for a High Level cost model, produced using the existing framework for Manufacturing Costs for Aeronautical products as proposed by Sun et al (2007).

The rationale behind the proposed Taxonomy for Process/Product Cost Elements and Data Types and their Levels is to provide a common set of definitions available to all of the stakeholders of the cost model and to standardise the task of effectively established the cost resources, level and type of the process cost elements that the cost model users or beneficiaries want the cost model to be developed for.

This Taxonomy was developed using a combination of features from domains other than cost estimating and modelling, including design engineering (feature-based design, design for manufacturability and design for assembly) and accounting (Activity Based Costing).

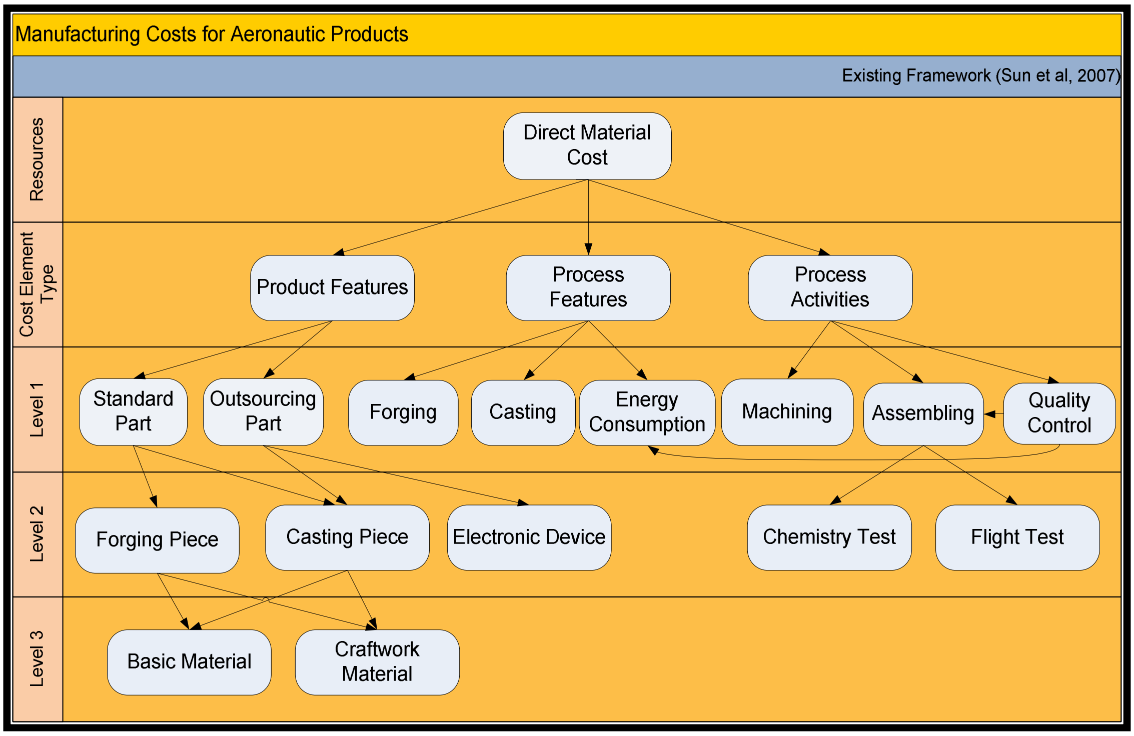


Figure 3.3 Breakdown for Direct Material Cost by Cost Elements and Levels (Sun et al, 2007)

3.4 Data Collection Techniques, Tools and Methods (DC-TTMs)

Data Collection methods have been proved to be useful in extracting information from a particular data source (Rush and Roy, 2001a); however, when used on their own they may not be sufficiently effective at capturing a vast amount of information from that particular data source (Roy et al, 2002). They have their weaknesses and limitations in respect to which type of information they can extract from the source(s), thus the cost model practitioner should expect to use and apply a combination of techniques, rather than relying on just a single one (Rowe and Wright, 1996; Hoffman et al., 1995; Rugg and McGeorge, 1999).

There are tools and techniques which fall under both Data Collection and Data Identification categories. In other words, Data Collection and Data Identification can sometimes overlap or take place simultaneously. This is the case of Critical Path Analysis, Process Flow Diagram, and Brainstorming, for instance.

In the same way, Data Collection tools (for primary data) can serve the purpose of Data Sources (as second hand data) from which the retrieval of information takes place by using other Data Collection methods or techniques.

As with Data Sources, Data Collection tools techniques and methods can be grouped into categories according to their basic characteristics, as described in the following sections.

3.4.1 Diagramming and Charting Techniques (DCT)

This category includes data flow diagrams to define business processes and process charts to describe a sequence of processes or operational stages. These techniques are tools to identify value added and non-value added activities such as wasted movement when performing a task. Diagramming techniques use visual notation systems, schematics and symbols, such as arrows and boxes to represent sequences, relationships and steps in a process. These are useful tools for designing and communicating the complexity inherent to process operations, and to facilitate the discussion of improvement measures and operation design.

They can be applied for data collection at different stages of the CMDP. At the early stages of the CMDP, when a top-bottom approach is more likely to be adopted, high level process flow diagrams and Outline process charts can be employed to represent the sequence of the process main activities. Similarly, at a lower level, activity charts and flow process charts can be employed to collect information on machine, material and labour.

Data types that can be identified and collected from the use of these TTMs include process activities from process level up to the operational task level. Process flow diagrams can be used to show the relationship among the steps in a process, or the components in a system. They are not limited to a physical flow map, as the flow can be related to time or to process steps and not only place.

3.4.2 Work Design and Methods Engineering (WDME)

This category differs from the ERMP techniques in that they look into the process tasks in much more detail, breaking down the jobs involved into small basic work elements. These techniques analyse the detail of the tasks involved in a job and the methods used in the process by following a work pattern:

- Select the task to be studied: this can be a single operation or a process
- Identify and record the facts
- Examine the facts

- Develop the new method
- Install the new method
- Maintain the new method

Some ERMP techniques are used to improve production methods for product components, while others contribute to the general operational environment. All are standard practice in production design (Robinson, 1999). Some of these methods include Work Measurement; Methods Study; Activity/Work Sampling; Checklists; Direct Observation; Photographical methods (Cyclegraphs and Chronocyclegraphs); Routing Sheet; Stopwatch Time Study; and most recently Video tape Recording and Film Analysis. Methods Study and Work Measurement are two principal activities of Work Study which originated in the work of Frederick Winslow Taylor and Frank and Lillian Moller Gilbreth (Kanigel, 1997).

These techniques are most suitable for the collection of data related to process activities down to the lowest level, i.e. work elements. Methods Study is applied to collect information on important process features including activities undertaken to perform the job and their sequence; type and number of operators involved and skills levels; facilities, equipment and tools to be used for the job; materials to be processed, consumed and moved.

Sources from which information can be gathered from by using these TTMs include process and products sources, and possibly synthetic sources. When used in conjunction with other techniques, they are useful instruments to measure, analyse and improve capacity utilisation and productivity.

3.4.3 Estimating Techniques (EsT)

These TTMs are part of the family of WDME category in terms of their application and principles; however they are grouped separately as they mainly collect secondary data and information. These include synthetic data provided by Time Study, MTM, Methods Study or Activity/Work Sampling. They rely greatly on the process knowledge and expertise as well as on the judgement of the subject using the technique; rather than on primary data collected from direct observation and time watch recording.

As with other Work Measurement methods, these are structured, estimating techniques in which a task is analysed into its basic component operations or elements. The time required to perform each constituent part of a task at a defined rate of working is estimated from knowledge and practical experience of the work and/or from synthetic data.

These estimating TTMs would normally be used for assessing work over a reasonably lengthy period of time, where it may be difficult and more expensive to collect the information required using other measurement techniques. Also, in some work environments the presence of an individual carrying out work measurement in the work place could be unacceptable still today. In these cases, estimating techniques may be an appropriate method to use, assuming someone with experience of the work is available to apply their experienced judgement. This may be work measurement personnel who have previous experience of that particular work.

3.4.4 Team Working and Consensus (TWC) Techniques

The importance of teamwork to the success of innovative projects is well documented by an extensive body of literature (McDonough, 2000; Hoegl and Gemuenden, 2001; Boyle et al, 2005; Barczak and Wilemon, 2001; Griffin, 1997), especially in areas such as new product development, project management, cycle time management, total quality management and continuous improvement.

Consensus could be defined as the process of achieving general agreement -reached by a group as a whole - on an issue under discussion or agreement in a judgment or opinion (Fink et al, 1984). Generally speaking, decision making under the team structure or group environment is achieved by consensus of some kind and to some extent.

Important factors which will define the effectiveness of Teamwork and Consensus (TWC) Techniques will include communication, balance of members' contributions, coordination, mutual support, effort, and team cohesion (Hoegl and Gemuenden, 2001; Schonberger and Knod, 1994).

3.4.5 Survey Research Techniques (SRT)

The broad area of survey research comprises any measurement procedures that involve asking questions of respondents. A survey form can be anything from a short paper-and-pencil feedback form to an intensive one-on-one in-depth interview.

Survey Types are roughly divided into two broad areas: Questionnaires and Interviews. Questionnaires are usually paper-and-pencil instruments completed by the respondents who are part of the sample (Oppenheim, 1992). Interviews are completed by the interviewer based on the respondent's answers. Surveys can include short closed-ended questions as well as broad open-ended ones. Nevertheless, open-ended questions tend to be shorter in questionnaires than in interviews.

Survey research has changed dramatically in the last two decades. There are automated telephone surveys that use random dialling methods. There are computerised booths and stands in public places that allow people to ask for input. A whole new variation of group interview has also developed such as Focus Groups and Nominal Group Technique (Ruyter, 1996), Delphi Methodology (Hsu and Sandford, 2007, Gupta and Clarke, 1996; Skulmoski et al, 2007; Rowe et al, 2005). With the Internet, web-based questionnaires and email surveys are evolving and sometimes preferred over mail surveys as they may offer more cost effective developing and operation costs.

The proliferation of mixed-mode surveys, where data is collected from respondents using different survey modes (web and telephone mode; mail and web mode; paper and telephone mode) is also increasing and gaining importance and credibility. Nevertheless, it has been recognised that there is always a higher rate of response from one type of survey over the other and when it comes to group administered questionnaire rather than mail survey.

In the same way, group interview or focus group are often more effective than the group administered questionnaires. In the latter, each respondent is handed an instrument and asked to complete it while in the room. Each respondent completes an instrument. In the group interview, the interviewer facilitates the session. Participants work as a group, listening to each other's comments and answering the questions. Someone may take notes for the entire group.

These techniques may be especially useful for developing cost models during the conceptual or definition stages for new processes or products, when there is little to none cost data and product or process information available. They may also be employed to define the model characteristics (cost model definition phase). These methods may prove to be effective when used working with multidisciplinary and cross-functional teams. A downside of these techniques, however, may be the subjective element involved in the responses

3.4.6 Engineering Research and Management Practices (ERMP)

In a broad view, this category involves techniques that analyse the detail of work flow in a process so as to define new approaches and, at a larger stage, to develop new methods. A typical example is the Value Stream Mapping (VSM) technique. It also includes certain specific techniques which can be used for the planning, management and progress control of projects. Network Analysis, Critical Path Analysis (CPA), and the American Program, Evaluation and Review Technique (PERT) are some of the classic methods of planning and controlling the progress of projects. These tools require the use of careful thought and the application of logic (Moder et al, 1983).

Some typical activities or tasks that might be studied using these techniques include cutting, finishing, assembling, purchasing, machining, testing and designing. These DC-TTMs could be effective procedures for collecting information from process, product and synthetic sources; specifically, those of the kind of process activities (earliest machining start time, earliest cutting finish time) and process features data types (critical paths, bottlenecks) (Wild, 1989 and 1995).

Like with the diagramming and charting techniques, these tools describe the tasks, activities and or process steps for a particular job in its current state. The basic difference lies in that because these project control and management techniques go a step further into the gathering of information (cycle times, start/finishing times, batch size) they offer the possibility of effectively assigning resources and identifying waste in the process, including bottlenecks, task slacks, and critical paths as part of a structured, logical and ordered plan relevant to most if not all development thinking.

The data is collected from many people. The techniques allow gathering information, experiences, and real time data from across the entire process and from different functions. Data from the machines is collected in real time from the machine operator, or from an attached computer database, from members of staff at different departments and centrally stored information sources. The future state map maybe collated by any (and more than one) member of the cost engineering/modelling team and by more than one level of employee.

The down point of these DC-TTMs is that the production of a current process state map is a time consuming process and may involve the return to the production floor to collate more information than what was previously considered to be needed.

On the other hand, these data collection techniques help to identify possible solutions to the highlighted problems on hand. From the perspective of the cost engineer, it will assist in identifying input data for the model (cycle times, batch size, change over), gaining an understanding of unfamiliar stages of the process (number of machines, inventory), and gathering information to validate the model later on (for instance, process efficiency).

Tables 3.5, 3.6 and 3.7 present the main features of the TTMs in relation to the level of detail of the cost model, the main data source categories and data types, the DC-TTMs can be used for gathering input information. Appendix E provides some samples of the Data Collection TTMs contained in the Library of DC-TTMs, Data sources and Data types with a detailed description of the steps involved and resources required to conduct the data collection task using each data collection tool, as well as potential data sources and data types the DC-TTMs can be used for.

DC-TTM Category	Level of Cost Model	
	High level	Low Level
Diagramming & Charting Techniques	•	•
Work Design and Methods Engineering		•
Estimating Techniques	•	•
Team Working & Consensus Techniques	•	•
Survey Research Techniques	•	•
Engineering Research and Management Practices	•	

Table 3.5 DC-TTMs Categories vs. Level of Cost Model

DC-TTM Category	Data Sources						
	Process	Product	Synthetic	Equipment/ Machine	Model based	Documentation Paper/ Internet	Heuristics
Diagramming & Charting Techniques	•	•		•	•		•
Work Design & Methods Engineering	•		•	•		•	
Estimating Techniques	•	•				•	•
Team Working & Consensus Techniques	•	•					•
Survey Research Techniques	•	•					•
Engineering Research& Management Practices	•	•	•	•	•	•	•

Table 3.6 DC-TTMs Categories vs. Data Sources (Developed Work)

Data Collection TTMs	Process Element		
	Product Features		
	Level 1	Level 2	Level 3
	Product	Component	Component feature
Diagramming & Charting Techniques	•	•	•
Work Design & Methods Engineering Techniques			
Estimating Techniques			
Team Working & Consensus Techniques	•	•	•
Survey Research Techniques	•	•	•
Engineering Research & Management Practices	•		

Data Collection TTMs	Process Features		
	Level 1	Level 2	Level 3
	Machine	Machine Assembly	Machine Sub-assembly
Diagramming & Charting Techniques	•	•	•
Work Design & Methods Engineering Techniques	•	•	•
Estimating Techniques			
Team Working & Consensus Techniques	•	•	•
Survey Research Techniques	•	•	•
Engineering Research & Management Practices			

Data Collection TTMs	Process Activities		
	Level 1	Level 2	Level 3
	Process	Process Operation	Operational Activity
Diagramming & Charting Techniques	•	•	•
Work Design & Methods Engineering Techniques	•	•	•
Estimating Techniques	•	•	
Team Working & Consensus Techniques	•	•	•
Survey Research Techniques	•	•	•
Engineering Research & Management Practices	•	•	•

Table 3.7 DC-TTMs Categories vs. Cost Data Elements (Data Types) (Developed Work)

3.4.7 Automated Data Collection (ADC) Tools

Automated Data Collection (ADC) tools are part of Shop floor Data Collection (SFDC) systems which take inputs from the shop floor in real time and allow feeding true measurements back into costing, scheduling and even maintenance planning.

The principle of collecting and making use of data immediately at the process or workplace is known as Process Data Collection (Bicheno, 2000), and usually involves the use of electronic devices. Collecting data accurately on a manufacturing operation, allows allocating costs correctly (for both standards and overheads) and reducing or eliminating problems associated with error rates, cumbersome operations and user dissatisfaction.

ADC tools can bring continuous measure of both shop and operator performance on each task compared against company standard times. SFDC also highlights problems related to design and tooling. This enables companies to attack these problems in an earlier stage and to get more accuracy on their costing.

The integration of ADC systems with the other manufacturing control systems (purchase order systems, ERP, MRP I, MRP II, EDI, among others) can bring more powerful advantages. This integration gives visibility of every stage of planning and execution. Integrated Work in Progress (WIP)/ADC systems allow collecting costs using standard times but also highlight variations in normal throughput which may indicate underlying problems.

Despite the advantages ADC tools can bring to a company, when they are implemented as an isolated manufacturing tool, or they are not fully exploited, it can result in a waste of time and money. Some examples of ADC systems include: Bar Coding; Radio Frequency Identification Transmitters; Magnetic Stripes; Smart cards and Optical Character Recognition (OCR).

3.4.8 Synergy of Methods: DCT and WDME; ERMP and SRT

Some techniques can be used in isolation. However, better results can be obtained when data collection tools are employed in combination with others. For instance, the use of Time Study together with VSM allows getting a better understanding of the wastes in the process (Bicheno, 2004).

In the same way, some TTMs act as data sources for other methods (Figure 3.4), in the sense that they will collect primary process and product data, which will be used as secondary data to be gathered by making use of another method. One of the inputs required for a Time Study will be the documented results (secondary data) of a Method Study for the job to be measured. Primary data is also required and will include tasks and their sequence collected from observations of the job to be studied, and time readings for the job to be measured from a stopwatch.

Subsequently, the output from the Time Study will be Standard Times and the documented work content for specific product and processes which will be used as primary sources of information by other TTMs.

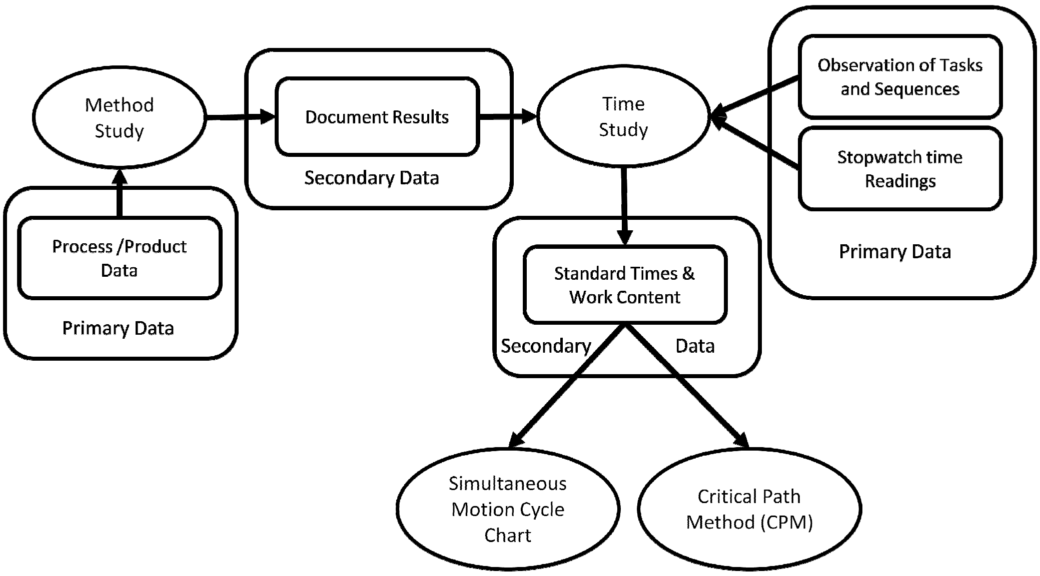


Figure 3.4 Primary and Secondary Data Collection (Developed Work)

3.5 Factors affecting the Selection of DS and DC-TTMs

3.5.1 Ability of Cost Engineers

It is not uncommon for the cost engineer to be presented with the challenge of developing cost models for processes or product not yet developed or for which he or she has little to no knowledge. Furthermore, it is nowadays common practice for these products and processes to be designed by teams of multidisciplinary or multifunctional members. It is then necessary to elicit knowledge, expertise and data from a variety of sources by using a range of different data collection methods and tools available to the cost engineer.

In cost estimating the application of a combination of experience, logic, judgement, common sense, and skill is required in order to generate a final cost estimate which is meaningful, timely and relevant (Rush and Roy, 2001a). According to Curran et al (2004), engineers apply these skills mainly when manipulating data from all of the functions that contribute throughout the product development cycle, interpreting predictions and modelling results, but not within the actual modelling process itself.

Hammaker (2000) states that the reasoning and logic skills an estimator develops, is not easily obvious because the knowledge that is required is complex and its sources are varied.

As far as Cost Modelling is concerned, Rush and Roy (2001b) point out the knowledge intensive nature of cost modelling and elaborate on the requirements to capture the skills and knowledge from a number of unrelated disciplines (Figure 3.5), in order to make sure the models are provided with the appropriate data that it requires. The authors sustain that this process of information and data elicitation relies on an accurate understanding of the product development capabilities available both at the company and at the supplier's base.

In addition, the skills and experience of the cost engineer will lead the selection of the most appropriate sources of data and information as well as the selection of the most suitable data collection methods and tools to be used to collate the input data for the model (Hollmann, 2006a).

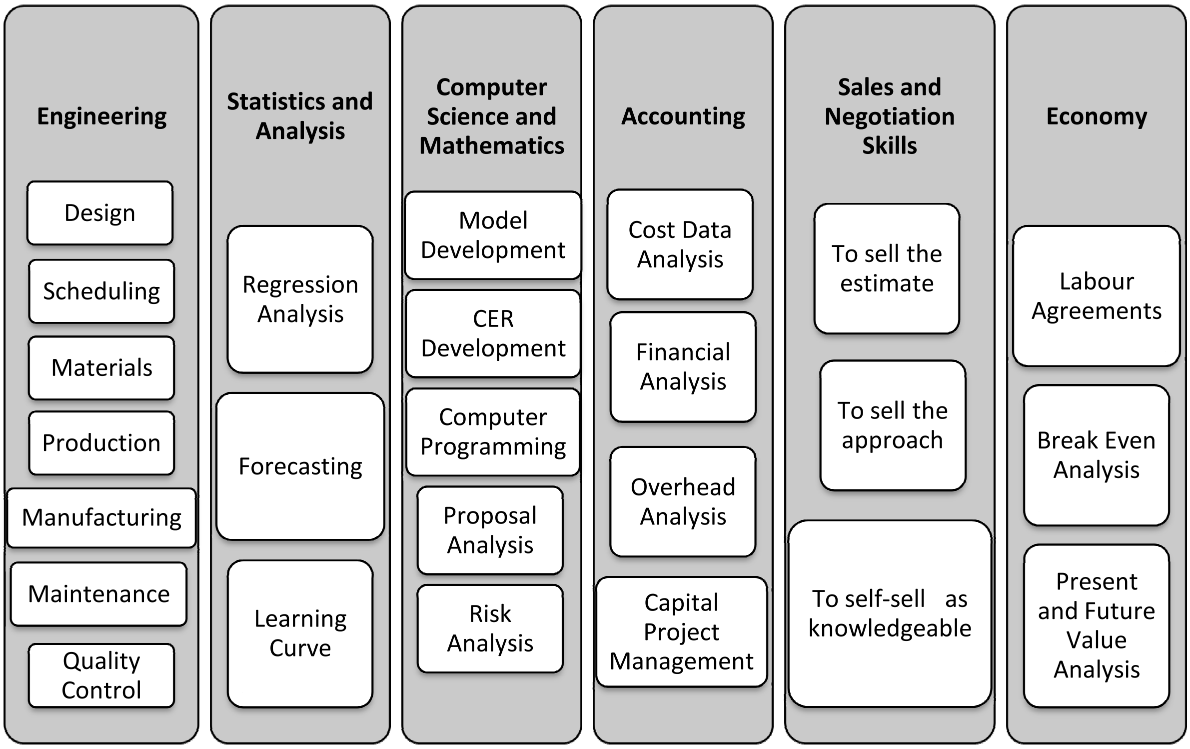


Figure 3.5 Skills and Knowledge Requirements for Cost Modelling and Estimating (Adapted from Curran et al, 2004; Rush and Roy, 2001a)

3.5.2 Effect of the Availability of Data on DS and DC TTMs Selection

The implications related to the effect of data availability and detail level of the model in relation to the data collection process of input data and information have been discussed in Chapter 2. This can also drive the selection of methods, including those for the identification and collection of data, as well as for the analysis of the information gathered.

During the New Product Development (NPD) process, cost data and information change along with its availability. These changes also have significant effect on the accuracy of the cost estimate and the total lead-time for its production.

The process and product characteristics as well as the cost model characteristics will influence the decision making process concerning the sources of information and the data collection methods to be employed to compile the required input data. For instance the actual process or schedules of the production or assembly operations involved would be appropriate for cost models of processes at a mature technology stage or products commercially available. As a result, data collections techniques and tools such as direct observation or video recording would be suitable for compiling cost data.

On the other hand, for processes and products at earlier stages of the development process, analytical estimating, brainstorming and interview would be more appropriate data collection tools as data may not be available and the only data sources on hand may be the process and product experts and standard times available from another source, or where no such times are available, they may be estimated based on experience of the work under consideration.

3.5.3 Purpose and Characteristics of the Cost Model

In addition to the model developer's skills and experience and data sources' availability, knowledge and understanding of the business objectives the model is supposed to serve along with other model characteristics, specially the time available to collect the data, expected model accuracy and model level of detail among others, assist in selecting the most appropriate data collection tools.

3.6 Influence of DC-TTMs in the Development of Cost Models

A central theme highlighted by the research literature is that of the difficulties associated with the selection of the most appropriate DC-TTM and its influence in the CMDP. Lengthy and complex procedures may add to the cost of producing a cost model. In addition, inadequate data collection approaches may have a negative effect on the accuracy and precision of the outcome of the cost model and, therefore, on the final estimate. As a result, a number of iterations around the steps of data identification and collection may take place.

Data handling and management may become difficult if the format of the data collected is not compatible with the cost modelling platform or ready available for the data analysis system. Therefore, careful consideration should be given to the selection and application of DC-TTMs in the CMDP in order to prevent costly and unnecessary pitfalls.

CHAPTER 4. RESEARCH METHODOLOGY

4.1 Introduction

This chapter describes the research methodology followed during the investigation and the different methods used at each step to accomplish the research objectives.

4.2 Scope of Research

The samples for this study were taken from a Universe consisting of industrial and academic experts in the fields of cost modelling and estimating with a variety of backgrounds and working at different organisational levels and business functions including management, production and operations, manufacturing, and design. The spectrum of industries included automotive, aerospace, process and the construction industry, based not only in the UK but also in North America, and Asia. To achieve the research objectives a mixed methods research design approach was adopted including the use of the internet and diverse support applications.

4.3 Research Methodology Design

4.3.1 Rationale

In order to accomplish the aim and objectives of the investigation, this study follows a multi-method approach (Brannen, 1992; Creswell, 1994; Sharkey and Sharples, 2001; Thomas, 2003; Creswell and Plano Clark, 2007). This variously called multi-methods (Brannen, 1992), multi-strategy (Bryman, 2004), mixed methods (Creswell, 2003; Tashakkori and Teddlie, 2003), or mixed methodology research (Tashakkori and Teddlie, 1998) is a combination of both quantitative and qualitative research methods which has become increasingly common and has gained strong support within the research community and several other applied fields (Tashakkori and Teddlie, 2003).

Creswell (1994) defines a multi-method or combined method study as the one in which the researcher uses a variety of methods and tools for data collection and analysis. It includes qualitative methods and quantitative methods (Creswell and Plano Clark, 2007). The analysis of these data often requires the application of statistical tools.

In a multi-method research study, the methods might come from a “within methods” approach (Brannen, 1992; Creswell, 1994), such as survey and experiments, at any one time for the same object of study. Or it might involve a “between methods” approach, based on the use of different methods (qualitative and quantitative data collection procedures) in relation to the same object of study (Jick, 1979). Examples include a survey and in-depth interviews. Table 4.1 lists the methods considered in this research investigation grouped in two categories, namely, qualitative and quantitative research tools.

Qualitative Methods	Quantitative Methods
Literature review Company Visits/Observation Open discussions/ semi-structured interviews Expert Opinion Focus Group Case Study	Questionnaire Survey Relational Matrix Consensus techniques Basic Descriptive Statistical Analysis

Table 4.1 Qualitative and Quantitative Methods considered in the research methodology (Developed Work)

Brannen (1992) ascertains that combined research approaches ensures the validity of data in a single unitary picture; allows to study different levels of enquiry and explore different aspects of the same problem. Greene et al (1989) also describe five purposes (advantages) of combining methods in a single study:

- Expansion: adding scope and breadth to the study
- Development: a first method is used sequentially to help inform a second method
- Triangulation: seeking convergence of results
- Initiation: allowing new perspectives and contradictions to emerge
- Complementarity: using the strength of one method to enhance the performance of another method.

A disadvantage of the Greene et al. (1989) scheme is its cautious and restricted approach, which limits the possible reasons for conducting multi-method research approach to only five reasons, although the authors' analysis showed that initiation was uncommon. Another disadvantage is that it only allows two rationales to be coded (primary and secondary).

The rationale for adopting a multi-method approach for this research investigation touches all five elements listed above, but mostly relies on complementarity of the methods and development of one method to inform a second method. For instance, the results from the Literature Review and Questionnaire Surveys (first method) were used to develop the categories of data collection tools and data sources to be employed during the Focus Group exercises (second method).

In this research investigation, this implies using and connecting the strength of different methods to address the complexity of the research topic; dealing with issues arising from the investigation; and also improving the effectiveness of methods that would follow after using a different method in the exploratory stage. It also responds to a combination of factors including the different data sets (literature review, observations, responses from semi-structure interviews questionnaires, small group discussions and focus group), sources, contexts and points in time the required information and data needed to be collected and analysed.

A more detailed but significantly less cautious scheme is presented by Bryman (2006). It was based on an extensive review (content analysis) of the sorts of reasons that are often given in both methodological writings and research articles (a total 232 analysed journal articles) for combining quantitative and qualitative research. Based on the work by Bryman (2006) and Greene et al (1989), Table 4.2 lists the reasons for combining qualitative and quantitative methods in this research investigation. The motivation for adopting this multi-method approach by the present research investigation is mainly based on explanation and complementarity, credibility, illustration, confirmation and discovery, and enhancement rationales (usefulness and expansion of findings).

In short, the mixing of data and the use of qualitative and quantitative research methods provide a better understanding of the problem than if either dataset had been used alone. Other benefits include the opportunity of testing different aspects and variables involved, then generalise the results of the investigation; giving a more complete picture of the problem, preventing bias either by the experts or the researcher (quantitative methods) and helping to measure qualitative findings.

	Qualitative Methods							Quantitative Methods				
Rationale	Literature review	Questionnaire Survey	Company Visits/Observation	Open discussions/ semi-structured interviews	Expert Opinion	Focus Group	Case Study	Questionnaire Survey	Relational Matrix	Consensus techniques	Basic Descriptive Statistical Analysis	Inferential Statistical Analysis
Triangulation or greater validity									•			•
Offset/Complementarity			•	•	•	•		•		•	•	•
Process										•		
Completeness	•		•	•	•						•	•
Different research questions								•				
Explanation	•			•	•		•				•	•
Unexpected results												
Development/Instrument Development	•	•						•	•	•	•	
Sampling		•						•		•		
Credibility	•		•	•	•		•					
Context					•		•					
Illustration	•		•	•	•						•	•
Utility or improving the usefulness of findings			•	•	•	•		•	•			•
Confirm and discover	•	•				•	•	•	•		•	•
Diversity of views	•					•			•	•		
Expansion, Enhancement or building upon quantitative/qualitative findings	•		•	•	•	•	•	•	•			•
Initiation	•	•						•	•			

Table 4.2 Rationale for adopting the multi-method approach (Developed Work)

In relation to the sequence, Creswell and Plano Clark (2007) define three ways in which mixing of qualitative and quantitative datasets can take place, namely: merging or converging datasets by bringing them together; connecting datasets sequentially by having one build on the other; and embedding one dataset within the other so that one type of data plays a supportive role for the other dataset.

The mixed-method research methodology used in this study was designed following the Exploratory Sequential Multi-Method (ESMM) research model (Creswell and Plano Clark, 2007). This sequential research design model involves collecting data in stages; this is: one data collection followed by a subsequent data collection. In this type of data collection, the quantitative and qualitative data collections are related to each other and not independent; one builds on the other. The weight given to the quantitative and qualitative data collection phases depends on the research question and the approach the investigator aims to emphasise. In the Exploratory Research Design, the first stage consists of the collection and analysis of qualitative data and the results from this stage are then used to influence the decisions upon which the design and results of the next stage will be built.

In this model, the qualitative component precedes and builds to the quantitative component. Qualitative data are first collected and analysed to explore the research topic in a small scale or few participants. Based on the qualitative results, a quantitative research instrument is developed, variables are identified, and research questions emerged and proposition for testing are stated. Those developments connect the initial qualitative stage of the research to the subsequent quantitative component.

The quantitative data are collected second in the sequence by single or multiple instruments (methods or tools) designed as a result of the findings, categories or relationships produced from the qualitative stage. These elements direct the research questions and data collection used in the quantitative phase. Using the previous example, the qualitative data collected from the Literature Review and Questionnaire I was then used to build up the Data Collection and Data Source Relational Matrix used during the Focus Group Exercises to collect quantitative information concerning the use of DC-MTTs and DS for developing cost models.

The motivation for this approach is that the qualitative data and their analysis provided a general understanding of the research problem and guided the design of quantitative research instruments to be implemented during the secondary quantitative phase. The quantitative data and their analysis helped to explain, justify and describe in more detail those results from the initial qualitative phase.

The selection of the sequential exploratory model was governed by the research problem, the study's aim and objectives, its context and the researcher's expertise and skills in the field of cost modelling. In addition to these factors, the choice of the research methodology was based on practical considerations including available time and resources; the relative weight (emphasis) of the quantitative and qualitative methods, and the timing (sequence) of the use of the collected data.

The separate and well-defined phases make this research design a straightforward approach. The sequential exploratory model usually gives emphasis to the qualitative component, the inclusion of a quantitative component can make the qualitative approach more suitable to quantitative-bias audiences (Creswell and Plano Clark, 2007).

Table 4.3 shows a breakdown of the research methods and research outcomes and how they feed into and relate to each other. Figure 4.1 shows the ESMM research model developed for this investigation. Table 4.4 describes in detail the EMMS methodology used in this investigation.

The present study does not include controlled experiments. In fact, no controlled cost modelling process experiment on any of the large-scale issues involved in this study was found in the literature. The data analysis methods used in this research include:

- Descriptive statistical analysis
- Case Study and inferential analysis tools such as Cause-Effect diagram, Pareto Analysis, Relational Matrix, Path Diagram and Paired Comparison Analysis

The conclusions from the study are based on reasoned explanations of the available/identified correlations.

The following sections describe the methods and tools used at each of the stages of the ESMM research methodology.

		Qualitative Methods							Quantitative Methods					Results/Findings/Outcomes				
		Literature review	Questionnaire Survey I	Company Visits/ Observation	Open discussions/ semi-structured Interviews	Expert Opinion	Focus Group	Case Study	Questionnaire Survey II	Relational Matrix	Consensus techniques	Basic Descriptive Statistical Analysis	Inferential Statistical Analysis	Proposed CMP Methodology	Validation of the proposed CMP Methodology	Refined Library of methods and tools (DC-TTMs)	Proposed CMP Scoping Framework	Process Scoping Framework Trials
Qualitative Methods	Literature review		•				•		•	•	•			•		•	•	
	Questionnaire Survey I				•							•		•		•	•	
	Company Visits/Observation						•		•					•	•	•	•	•
	Open discussions/ semi-structured Interviews						•		•	•	•			•	•	•	•	•
	Expert Opinion		•	•			•	•		•	•	•	•	•	•	•	•	•
	Focus Group									•	•	•	•	•	•	•	•	
	Case Study														•			•
Quantitative Methods	Questionnaire Survey II													•		•	•	
	Relational Matrix															•	•	
	Consensus techniques													•		•	•	
	Basic Descriptive Statistical Analysis								•	•				•		•	•	
	Inferential Statistical Analysis													•		•		

Table 4.3 Relational Matrix of Research Methods and Research Outcomes (Developed Work)

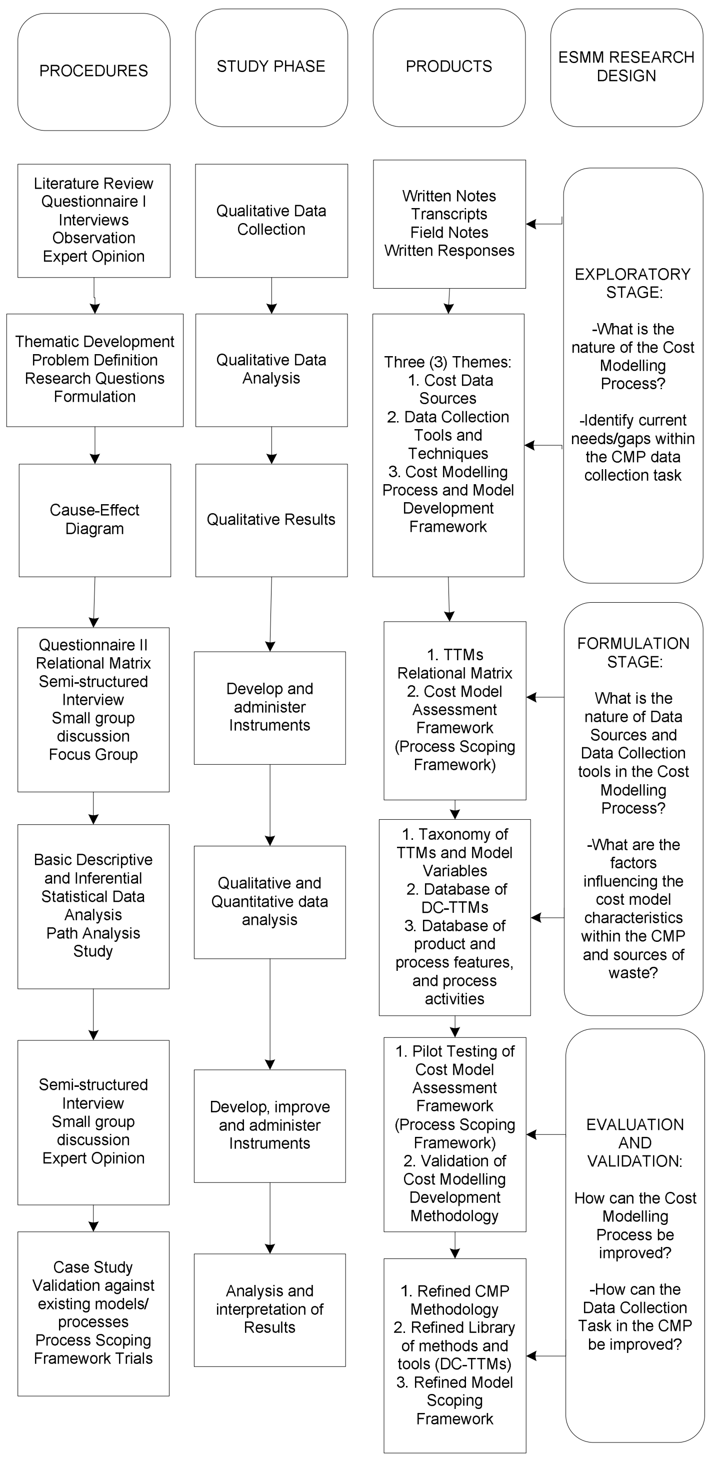


Figure 4.1 Schematic Representation of the ESMM Research Methodology developed and adopted for this research investigation (Developed Work)

RESEARCH STAGE		
EXPLORATION		
WHAT (Method)	WHY (Aims)	HOW (Description)
Literature review Company visits Open discussions/ semi-structured interviews Expert opinion from Professional Institutions and SIG Groups	To establish a firm basis for research To formulate Research Questions and a viable direction for the research To outline research aim and objectives	Publications and formats e.g. theses, books, journals, professional magazines, manuals, company procedures, and material from Professional Institutions websites were revised. Academic and Industrial experts were consulted. Background work in the subject reviewed.
Open Questions Questionnaire (Questionnaire I) Follow-up Semi-structured interviews Qualitative Analysis	To identify problem areas in the CMDP Identify the factors influencing the cost model characteristics within the CMP and potential sources of waste To obtain an insight view into traditional methods and tools for data identification and collection used for cost models To identify potential courses of action within the DC task to improve the CMDP	Through face to face interviews with industrial experts in cost engineering Cost models for manufacturing processes in Aerospace were discussed Cause-effect diagram of main issues and their causes
FORMULATION		
WHAT (Method)	WHY (Aims)	HOW (Description)
Close Questions Questionnaire (Questionnaire II) Follow-up Semi-structured interviews	Broaden scope in terms of audience (population sample) and type of industry Narrow approach in terms of issues addressed: cost model characteristics and purpose, data sources and data collection process in the CMDP Identify factors that influence the development process of cost models, including model purpose and business objectives the cost model aims to serve.	On-line Questionnaire Distribution list built from Company Databases, Professional Bodies, Institutions and Organisations in the cost engineering field Interviewing cost modelling practitioners
Focus Group Exercise Small Group Discussions	To categorise Cost Information Sources and Data Collection Tools, Techniques and Methods (DC-TTMs) Define criteria for data types and levels of detail Identify common process and product features, and process activities used as input data for cost models	Completing the DS-DC Relational Matrix Completing the DS-Data Types Relational Matrix Participants included industry-based cost modelling practitioners and academic staff working in the area of cost modelling Combination of Consensus techniques (Brainstorming and Paired Comparison) in small group discussions
Basic Descriptive and Inferential Statistical Analysis, including: Average, Error and Range Pareto Analysis Scatter Diagrams Histograms Path Analysis Study	Identify DC-TTMs with potential applicability in CMDP Identify possible links between DS and DC-TTMs Identify possible links between DC-TTMs and data types (product and process features and process activities) at different levels of details	Data preparation (cleaning and organising data for analysis) Using commercially available statistical packages
Relational Matrix	Identify the relationship between the elements of the MSF (process and product features and cost model characteristics)	Using Brainstorming and Consensus techniques in small group discussion
EVALUATION and VALIDATION		
WHAT (Method)	WHY (Aims)	HOW (Description)
Proposed CMP Methodology Outline Refined Library of methods and tools (DC-TTMs) and data types Proposed CMP Scoping Framework	Select and implement solutions to reduce/ eliminate the causes of problems identified during the Analysis phase Set measures to sustain improvements over time and make suitable recommendations Verify (provide evidence of) sustainability	Case Study Validation against existing models/processes Process Scoping Framework Trials Validation of the proposed improved Cost Model Development Methodology

Table 4.4 Description of Methods used in the ESMM based Research Methodology and work undertaken (Developed Work)

4.3.2 Literature Review and Company Visits

An initial literature review was conducted in order to explore and identify current trends, practices and approaches for cost modelling, as well as to establish the gaps in the CMDP. The literature review also included published case studies and historical data.

The use of the internet and its applications for research purposes has expanded since its creation. On line resources including professional discussion groups and special interest groups from a variety of industry sectors, also contributed to identify and explore these issues, including the identification of existing approaches to the CMDP. The application of traditional techniques and new tools used in the generation of cost models and for gathering cost data were also identified.

The Literature review and the analysis of existing cost models, where mainly discussed and presented on Chapters 2 and 3. The Literature review was followed by survey questionnaires (I and II) and face to face interviews with academic and industrial experts in the area of cost modelling and estimating. The main purpose of undertaking the first questionnaire was to complete and to validate the outcome of the systematic literature review.

4.3.3 Questionnaire I and Interviews

A questionnaire is one of the main methods of primary data collection and a way of obtaining real life responses (Adams, 2008). An open question paper-based survey was prepared, tested and applied to complement the findings from the literature review and obtain an in-depth understanding of the CMDP.

It is commonly agreed that the selection of the right participants is highly critical to the success of any survey exercise (Skulmoski et al, 2007). Questionnaire I was developed and applied to a selected group of companies in the aerospace sector and particularly to a small sample, consisting of practitioners in cost engineering, analysis and estimating. The focus was on the stages of the CMDP in particular the data collection stage, its tools and techniques.

The objective was to identify the needs for improvement in the CMDP and to review the development approaches used for building models. Informal semi-structured interviews were then conducted. The limitations associated with the level of confidentiality and the commercial sensitivity which typically surrounds the cost estimating subject increased the non-response rate. These interviews focused on determining the amount and degree of detail that could be obtained from the use of a more specific and detailed (close question based) questionnaire and interviews. A sample copy completed for one of the models from the participants companies can be found in Appendix A1.

4.3.4 Survey Questionnaire II and Interviews

Based on the outcomes from Questionnaire I and the literature review, Questionnaire II was developed and administered. This was an electronic mail (email) and mail (postal) self-administered questionnaire. It asked participants to rate the importance of the cost model characteristics as identified from the literature review and Questionnaire I.

Despite the benefits of using the questionnaire survey as a research method, the increased respondents choice, and the commercially sensitive nature of the research topic may have a negative effect on the response rate. It has been recognised (Dillman et al, 2009) that, to overcome this and other challenges, it is necessary to simplify the task of accessing and completing them, including offering multiple survey modes, i.e. mail and internet based survey questionnaires, even if this increases the possibility of mode effects in the data (Dillman and Christian, 2005).

The main reasons for adopting an on-line based survey questionnaire for this study included lower associated labour and financial survey costs; possibility of a wider audience (sample size); reduce non-response and coverage error; to improve timeliness and response rate (questionnaires are completed at the respondents' convenience); no need for manual data input for data analysis which minimises measurement error (Sudweeks and Simoff, 1999; Creswell and Plano Clark, 2007). Other benefits included anonymity as it is greatly assured and respondents are free to provide objective views on sensitive issues (Neuman, 2005; Sarantakos, 2005).

The Internet has proved to be a useful mode for conducting surveys targeted at very specific populations such as certain professionals; however, it also has significant coverage gaps in the general population (Best and Krueger, 2004). In order to overcome this barrier, the possibility of a mail version of the questionnaire was provided as an option to respondents. A copy of Questionnaire II's template is available in Appendix B1.

A wider approach was adopted for this phase. This time the work carried out focused on particular issues identified from the analysis of the former survey, including cost model purpose, objectives and characteristics; cost data types; sources of data and cost information required for building cost models; factors affecting the developing process; and most importantly, the identification of current tools and techniques for cost data collection and identification.

The sample consisted of practitioners in the areas of cost estimating, cost engineering and modelling from a broader spectrum which included the automotive, aerospace, construction and process industries, based not only in the UK but also from North-America and Asia.

The participants were identified and selected from company databases including FAME and KOMPASS, and from online SIGs, member directories and discussion forums from professional institutions, associations and Government organisations specialised in cost modelling and estimating, as shown in Table 4.5.

Institution/Organisation	Website
Association for the Advancement AACEI, West Virginia, USA	www.aacei.org
The Association of Cost Engineers (ACostE), Cheshire, UK	www.acoste.org.uk
Society of Cost Estimating and Analysis (SCEA), Viena	www.sceaonline.org
International Society of Parametric Analysts (ISPA), Viena	www.ispa-cost.org
International Cost Engineering Council (ICEC), Deakin West, Australia	www.icoste.org

Table 4.5 Professional Institutions and Associations linked to Cost Modelling and Estimating Activities (Developed Work)

This work also provided the basis for the MSF, as an improvement tool to overcome some identified issues and pitfalls related to the CMD tasks. Questionnaire II was accompanied by follow-up semi-structured interviews with cost engineers at selected participant companies and focused on clarifying issues which could not be addressed by the questionnaire due to its nature (closed question); in particular those issues related to the CMDP DC stage, its tools and techniques.

4.3.5 Cause and Effect (Fishbone) Diagram

Fishbone diagram, which is also known as The Cause and Effect diagram, Root-Cause diagram or Ishikawa diagram (Wild, 1989 and 1995) was used for the analysis and presentation of the data from the questionnaires and the follow up interviews. This tool helps in establishing the potential root causes of a precisely specified problem.

The information collected from Questionnaire I, interviews; online SIGs, discussion forums and websites for institutions, Associations and Government organisations was assessed using the fishbone diagram. This data was mainly of a qualitative nature and aimed to set the basis for identifying the current state of the CMDP and potential causes of pitfalls and performance deficiencies in the process; defining the research problem and outlining the research aim and objectives; and providing the basis and justification for Questionnaire II.

4.3.6 Focus Group Exercise and Small Group Discussion

The Focus Group approach was adopted in the Formulation stage of the ESMM research model to gather information and complete the matrices as described in the following sections. This technique offers the following advantages:

- Empowering research participants, who can become an active part of the analysis process.
- Enabling the development of particular views and perspectives as a result of talking with other people who may have similar experiences or expertise.
- Encouraging participation from individuals averse to be interviewed on their own.
- Helping to explore and clarify views in ways that would be less easily accessible in a one to one interview.

Two approaches were also used for collecting information at this stage: Brainstorming and Paired Comparison (PC).

4.3.6.1 Brainstorming and Paired Comparison

During this phase, small group discussion assisted in establishing the criteria for defining data elements, data types and detail levels (Chapter 3). In order to verify the validity of the definitions and characteristics of the identified data types, a combination of knowledge acquisition techniques (Wagner et al, 2002) and consensus ranking techniques (Shi et al, 1996), consisting of Brainstorming and PC, in the context of small group discussion were conducted. Common process and product features, and process activities used as input data for cost models were identified using the proposed taxonomy (described in Chapter 3). This exercise resulted in the generation of a generic Library of process and product features, and process activities for common manufacturing process.

Brainstorming allows the generation of ideas on a particular topic without criticism or judgement, while PC is a prioritisation and consensus technique used to enable a team to analyse and come to a decision based upon voting (Glickman, 2001). Brainstorming was used to identify the dependant and predictor variables for each particular resource at different levels of detail by allowing participants to express their opinion freely and hence collect the major number of ideas. These were then fed into the PC Voting Matrix for ranking.

The Paired Comparison (or Pair-wise Ranking) technique was selected over other consensus techniques such as:

- Nominal Group Technique (NGT) (Delbecq and Van de Ven, 1970; Delbecq et al, 1975; Jones and Hunter, 1995; Ruyter, 1996; Sample, 1984; Van de Ven and Delbecq, 1974)
- Analytical Hierarchy Process (AHP) (Labib et al, 1998; Partovi et al, 1990; Partovi, 2001; Razmi et al, 1998; Saaty, 1980, 2006 and 2008; Rangone, 1996; Yusuff et al, 2001; Bhutta and Huq, 2002)
- Delphi Process (Barker and Burns, 2001; Jones and Hunter, 1995; Hsu and Sandford, 2007; Gupta and Clarke, 1996; Rowe and Wright, 1996 and 1999; Rowe et al, 2005; Skulmoski et al, 2007; Linstone and Turoff, 2002; Martino, 2002)

These tools are for gaining (even forcing) group consensus among experts on options or alternatives, based on specific decision criteria which have been already weighted, ranked and/or pre-established, and are weakened by not allowing group members to discuss issues.

PC Analysis, on the other hand, allows taking into consideration all possibilities disregarding a particular decision criterion (McCormick and Bachus, 1952).

PC can also be used by individuals; however, it is more commonly used by a team. Only one questionnaire could be filled using the consensus opinion of the team; hence, less time consuming as the number of rounds is limited to one; it is not necessary to use a high level of programming or data analysis expertise to prioritise the range of options or root causes; it does not require a highly structured meeting to gather information and allows verbal interaction; changes in opinion or judgement are less likely to occur as the number of iterations or rounds could be limited to one (Rowe et al, 2005).

As stated by Triantaphyllou et al (1997), the method also allows to determine the relative importance of each of the alternatives given from a list of items in terms of each criterion involved in a given decision-making problem or situation.

The PC Matrix applied to the Process of Wing Box Fabrication is presented in Appendix C3. The same procedure was applied to other similar processes.

4.3.6.2 Relational Matrix or Design Structure Matrix (DSM)

Since its creation in the context of process management and with a first published formulation in 1981 by Donald Steward (Steward, 1981), the concept of Design Structure Matrix (DSM) or Relational Matrix has evolved and extended to different application grounds (Souza Neto, 2008; Danilovic and Browning, 2007; Shamsuzzoha and Bhuiyan, 2005).

DSM is commonly applied in identifying relationships of dependency between the sub parts of a system (Browning, 2001). According to Yassine (2004), traditional project management tools, which include PERT, Gantt Charts and Critical Path Method (CPM), do not effectively address problems arising from the complexity of the systems under consideration. These tools are based on diagramming representation of the systems and, for complex systems, it is difficult to analyse the interactions this way (Gebala and Eppinger, 1991; Bartolomei, 2001; Smith and Eppinger, 1997). Furthermore, despite allowing the modelling of sequential and parallel elements (processes, tasks or activities), these tool fail to address interdependency (feedback and iteration), which is frequent in complex PDPs (Browning and Eppinger, 2002). DSM deals with this issue.

This method differs from traditional tools because it focuses on representing information flows rather than work flows. The DSM tool can be defined as an information exchange model which allows the representation of complex relationships. Afsharian, et al (2008); Danilovic and Browning (2007), Gebala and Eppinger (1991), Souza Neto (2008), Sosa et al (2005) and Yassine (2004) provide basic concepts, description of the methodology involved in using the tool and case studies in different domains.

In project planning and management, particularly in engineering, the use of DSMs has contributed to considerable reduction in total project time, optimising the relationship of dependency between the activities described in the matrix, with the added value of providing an easy, quick and intuitive view of the planning process and its components interdependencies (Pieroni and Naveiro, 2006; Manzione and Melhado, 2007). Matrix representation has the advantage of allowing capturing significantly more information than other tools in an easily usable form; enabling the management and handling of measures of tasks interdependence and providing enough flexibility to be used in many scenarios and at different levels.

The Relational Matrix tool was used for both collecting information on the relationship between data sources and data collection tools and then for collecting information on data sources and cost data elements including dependant cost elements and predictor cost elements (types and levels). The analysis of the results produced the potential data collection methods which can be used with each particular data source.

A modified relational matrix (DS-DC Matrix) containing the identified data sources (DS) and DC-TTMs was prepared to examine the ability of the data collection methods to extract information from each particular data source (Appendix C2). Figure 4.2 shows the top right quadrant of the matrix.

		1 - Process Sources	Actual Process	Video of Process	Process Expert	Similar Processes	Visual and Control Tools	Computerised Planning Systems	Process controllers/automatic condition monitoring
	Data Sources		1.1	1.2	1.3	1.4	1.5	1.6	1.7
	Data Collection Tools								
A	Diagramming & Charting Techniques								
A1	2D & 3D Diagrams								
A2	Flow diagram								
A3	Flow process chart (m/c,matl,men)								
A4	IDEF process chart								
A5	Multiple activity chart								
A6	Outline process chart								
A7	Simultaneous motion cycle chart								
A8	String diagram								
A9	Travel chart								
A10	Two-handed process chart								
A11	Mind Mapping								
A12	Tree Diagram								

Data Sources and Data Collection Matrix

Figure 4.2 Sample of the top right quadrant of the DS-DC Matrix (Developed Work)

The different DSs identified from the investigation were grouped into categories according to a set of criteria (Chapter 3) and listed along a single column. The DSs are listed by category in Table 4.6.

The DC-TTMs were arranged along the top row of the matrix. The DC-TTMs were also grouped into categories (Table 4.7) as per the Taxonomy described in Chapter 3.

In the matrix, each relationship was evaluated by entering a 1 in the cell. If no apparent relationship was perceived the cell was left blank. In binary DSM notation, the matrix is populated with ‘ones’ and ‘zeros’ (or X marks and empty cells) and a single attribute is used to convey relationships between different system elements. The ‘existence’ attribute signifies the existence or absence of a dependency between the different elements. The attribute was the capability of each DC-TTM for extracting suitable information from each of the data sources. The system shall produce the DC-TTMs that can be used with each DS, with the analysis determining the most significant data collection method.

Category	Data Sources
1 - Process Sources	1.1 Actual Process 1.2 Video of Process 1.3 Process Expert 1.4 Similar Processes 1.5 Visual and Control Tools 1.6 Computerised Planning Systems (ERP, MRP I, MRP II, MPS) 1.7 Process controllers & automatic condition monitoring (ii)
2 - Synthetic Sources	2.1 Synthetic Standards (Standard Data) 2.2 PTMS Systems (MTM, MOST, MSD, MST)
3 - Product Sources	3.1 Costed Components 3.2 CNC Programmes 3.3 CAD Files 3.4 Product Specification 3.5 Bill of Materials (BOM) 3.6 Engineering Drawings
4 - Equipment Sources	4.1 Equipment Specification 4.2 Maintenance Manuals 4.3 Operating Manuals 4.4 Training Manuals 4.5 Equipment performance records
5 - Model Based Sources	5.1 Process Models 5.2 Empirical Laws 5.3 Physical Models
6 - Paper/Internet Sources	6.1 Literature reviews 6.2 Departmental records 6.3 Operator's Black Book 6.4 Quality manuals/reports 6.5 Shopfloor Documentation, Planning & Control Sheets 6.6 Patents 6.7 World Wide Web (WWW)
7 - Heuristic Sources	7.1 Rules of Thumb 7.2 Personal Judgment, Common sense, Logic 7.3 Expert experience/opinion

Table 4.6 Data Sources listed by Categories (Developed Work)

Categories	Data Collection Tools
Diagramming & Charting Techniques (DCT)	2D & 3D Diagrams Flow diagram Flow process chart IDEF process chart Multiple activity chart Outline process chart Simultaneous motion cycle chart String diagram Travel chart Two-handed process chart Mind Mapping Tree Diagram
Work Design and Methods Engineering (WDME)	Activity/Work Sampling Checklist Chronocyclegraphs Cyclegraphs Direct observation Video tape recording/Film analysis sheet Stopwatch Time Study Routing Sheet
Estimating Techniques (EsT)	Analytical estimating Category estimating Comparative estimating Judgemental analysis technique
Team Working and Consensus (TWC) Techniques	Brainstorming Creative thought Decision modelling
Survey Research Techniques (SRT)	Interview Questionnaires
Engineering Research and Management Practices (ERMP)	Experimentation (operational experiments) Network analysis Program Evaluation and Review Technique (PERT) Critical Path Method (CPM) Value Stream Mapping

Table 4.7 Data Collection Tools and Techniques by Categories (Developed Work)

Another matrix (DS-Dtype Matrix), containing the different data types (Dtypes), their levels and the different resources which may require a cost model was also developed (Appendix C1).

The purpose of this exercise was to evaluate and identify the potential data sources for different data types at different levels of detail. These inputs were expected to be used to establish some rules for the selection of DS and DC-TTMs according to the characteristics of the specified product or process and those of the required cost model. Expert opinion and experience was employed to determine the most suitable DS (3 maximum) from a provided list, considering the stage of the process/product and the resource to be costed as decision-making criteria.

When building a DSM, the success of the method is determined by the accuracy of the dependence relationships collected and by appropriate system decomposition (subsystems, levels or modules). One way of achieving this is by using two main approaches:

- Converting existing documentation: design manuals, process sheets, operation schedules, product documentation, IDEF models.
- Structured expert interviews.

A hybrid approach was adopted in this investigation, where a starting DSM was built from existing documentation (literature review), and then a subsequent step of small group expert interviews was used to supplement and validate the initial DSM.

In the second step a group of cost estimating and engineering experts, from different functional groups of the participant organisations, and academic staff working in the area of cost modelling, were asked to verify the list of the different data types, levels and sub-levels that comprise the matrix system as a whole.

After the pilot exercise and follow up discussions with the contributors, the improved matrices were completed using the Focus Group technique and the expertise of the academic staff and the industrial experts from Rolls-Royce plc, BAE Systems Airbus, BAE System Military, Hyde Group Ltd and Diamonite Aircraft Furnishing Ltd.

Group interaction can be a major disadvantage of Focus Groups as it may inhibit the exchange of opinions (Ruyter, 1996). The causes may include: status, pressurising conformity, group dominance by strong personalities, lack of variability in points of view, and knowledge and cultural differences between respondents (McDonald, 1993; Ulmenstein, 1995). One of the basic factors or recommendations in Focus Group, therefore, is that experts' judgmental predictions should be made independently because of evidence that group pressure and conditions during group consensus exercises can harm the accuracy of the results.

To overcome the above limitations and reduce any possible group pressure, the researcher provided the required information, clarified the procedure and answered questions while conducting a couple of rounds. The experts then completed their respective matrix forms individually.

The analysis of the data obtained from these exercises was used to identify possible links between the DS, data types and DC-TTMs for the generation of cost models. It also allowed exploring what new methods could be introduced within the CMP for improving the tasks of data collection.

4.3.6.3 Path Analysis Diagram

The results from the PC exercise on the identification of product and process features and process activities were analysed using a simplified version of the Path Analysis Method (Alwin and Hauser, 1975).

The intention was to use a visual representation or mapping of the relationship between the predictor variables at different levels of detail. The analysis assisted in building a library of predictor variables for common manufacturing process for which cost models can be built, as described in the Case Studies 1 and 2 in Chapter 6.

Future work could involve quantifying, interpreting and deriving the equations or algorithms to explain the relationship between the variables involved in the development of the cost model by using the Path Analysis Technique to a full extent (Werts and Linn, 1970; Burns and Clemen, 1993).

4.3.6.4 Descriptive Statistical Analysis

Basic descriptive statistical analysis was employed for the examination of the information collected from Questionnaire II and from the Focus Group exercises on DS and DC-TTMs, and on DS and Data Types. Inferential statistical analysis such as Pareto Analysis and Scatter diagrams were also considered.

For the analysis of the data collected from the matrices, techniques such as ‘normalisation’, ‘shifting’ and ‘scaling’ were used, in order to eliminate possible false trends and to help to visualise the effects of the different variables.

Percentages were used as the single unit of measurement for the results from the data analysis of the DS-DC TTM matrix. As there is a single unit of measurement for all the criteria, normalisation was necessary for converting the measurement of alternatives to relative values, synthesising and obtaining the right answer (Saaty, 2006).

Normalisation is always needed when the criteria depend on the alternatives. In this case, the categories for DS and DC TTMs had different number of alternatives and no restriction on the number of alternatives that could be chosen at any one time. Therefore, by adding the measurement values under each DC-TTM and dividing it by the sum of the measurements with respect to all the other criteria measured on the same scale, the priority or score of that criterion for that unit of measurement was obtained.

The results were analysed and discussed by category of DS and DC-TTM and Data Types and their respective levels. The Pareto Principle was used in the analysis of the data collected from the DS-DC matrix. Based on the Pareto principle, which states that 20 per cent of the causes usually account for 80 per cent of the effects, the discussion on the outcomes from the analysis of the DS-DC matrix focused on those DC-TTMs which cumulative (combined) percentage scored of 80 per cent. This is the typical distribution in process and product improvements.

The analysis of the results produced the potential DC-TTMs which can be used with each particular DS. The DS-DC database has been improved and updated based upon the outcomes from the focus group exercise. Samples of the entries from the DS-DC database are included in Appendix E.

Histograms were used for the analysis of the DC-Dtype matrix, to show the relative frequency the different categories of DS could be used to identify predictor variables (product and process features and process activities) for the different cost resources at different levels of detail and at different stages of the product lifecycle. Initially, Scatter Diagrams were considered as the tool to identify the relationship or correlation between Dtypes and DC-TTMs. However, because of the different conditions under which the data sets where collected and because there were different criteria used (DS vs. DC-TTM and DS vs. Dtype) there was felt that any relationship was not going to be a real correlation between the variables involved (DC-TTM vs. Dtype). The main findings from this exercises and the rest of the work undertaken are discussed in the following Chapters.

4.3.7 Proposed Cost Modelling Methodology

The foundations for the proposed CMD Methodology consist of a compromise between the traditional approach to cost modelling and a new improved Methodology which includes tools such as a Cost Modelling Framework and the use of the PC Matrix. the CMP. The proposed Cost Modelling Methodology, whose improvements emphasises on the Data Identification and Collection stages of the CMDP, is fully described in Chapter 5.

4.3.8 Design of the Model Scoping Framework (MSF)

The Model Scoping Framework is integrated into the proposed CMD Methodology, as an application tool in the cost model definition stage. The objective of the MSF is to assist cost engineering practitioners on the task of defining the model purpose, characteristics and outcomes, and to advise on the selection of the most appropriate data sources and data collection methods to be used.

The elements of the MSF were carefully chosen using the information collected from the Literature review, Questionnaires I and II and the Focus Group exercises. Once selected, the relationships between these elements were identified using DSM. Initially, it was the intention of the investigation to weight and rank the MSF elements using the PC method to assess their contribution and importance.

PC Analysis assists in setting priorities where there are completely different options for resources or factors or where there is conflicting demands or requirements, without considering any particular criteria. This analysis was expected to help to refine the specifications of the MSF by comparing and weighting the different factors to take into consideration when scoping a process or product which a cost model is required for; consequently, providing a way for looking into the relationships between the different components/elements of the Framework. However, the Relational Matrix or DSM was used instead because of its additional advantages.

As previously stated, DSM matrices are useful because they can represent the presence or absence of a relationship between pairs of elements of a system. A major advantage of the matrix representation over diagram based tools is in its compactness and ability to provide a systematic mapping among system elements that is clear and easy to read regardless of size. In other words, DSM overcomes the size and complexity limitations of other methods, such as PC, so that by following the structure of the information flow, it is possible to map the relationships between the elements of the system or process in a precise order which makes interdependence explicit.

Another reason for using DSM over PC is that DSM matrices enable to develop a holistic understanding of a system (Bartolomei, 2005). Therefore, DSM was used to collect information regarding the effect of each of the factors included in the MSF over the others (synergy or detrimental effect), as it was considered a more fundamental issue establishing a holistic qualitative understanding of the system and the type of effect of the elements on each other, than examining the dynamics of the system by weighting the magnitude of the effect of the elements on each other. This could be a subject for another investigation or future work.

The MSF is nested within the “Model Define” step of the Proposed CMD Methodology and is discussed in Chapter 6 (Figure 6.2).

4.3.9 Validation of the Proposed CMD Methodology

For the validation of the proposed CMD Methodology, an industrial Case Study was used as analysis tool.

The primary form of data analysis in the Case Study is the reflection by the researcher on their own experience. A variant of the method is known as the talk-through case study, also referred as case study analysis (Travers, 2001). This involves the use of real cases which an interview could focus on. In this case, the expert (interviewee) goes through a past or current case where the elicitor (interviewer) has the opportunity to focus the questioning on that case. Talk-through case study analysis is suitable to elicit facts, casual and procedural knowledge from experts. One of its main advantages is that the use of a case, which experts are familiar with already, may ‘trigger’ the experts’ memory to reveal to the elicitor facts that otherwise would be difficult to recreate in their answers.

The CMD methodology was validated using cost models at Rolls-Royce Ltd in Derby. The proposed Methodology was discussed with Neil M Keenan Value Engineer and Materials Specialist at the Value Improvement Division at Rolls-Royce Plc after the process was followed for the development of cost models required for a set of engine components. The Outline and Validation of the Proposed Cost Modelling Process Case Study is discussed in Chapter 6.

4.3.10 Validation of the MSF

The PSF was verified and validated using existing and under-development industrial processes, including Composite DDF process (Conceptual Stage, BAE Systems), and O-ring manufacturing (Established Commercial Process, Rolls-Royce Plc), and CNC Machine Centre (Prototype Stage, BAE MA&A, now Military Air Solutions). The rationale for producing the MSF is discussed in Chapter 6.

CHAPTER 5. ANALYSIS AND DISCUSSION OF RESULTS.

5.1. Introduction

This chapter involves the analysis and discussion of the results obtained from the first (EXPLORATION) and second (FORMULATION) stages of the research methodology.

5.2. Exploration Stage: Literature Review, Questionnaire I and Interviews

5.2.1 Literature Review

No specific limit was set in terms of date of publication during the search process but the references found were mainly all published between 1999 and 2009.

Many articles in cost modelling and estimating have largely focused on estimating techniques and methods. This situation may suggest that in the cost modelling and estimating community the main factor to consider when estimating accurately is largely based around the technique being used (Lederer and Prasad, 1998) rather than on other elements such as the identification and collection of cost data and information, despite the importance and effect of data collection on the cost modelling process being stressed by some authors (Liyanage and Perera, 1997, 1998, 2000 and 2001; Meisl, 1988; Walkerden and Jeffery, 1997).

The authors have also pointed out, that data collection for decision making and support is expensive, labour intensive and, as stated by Masticola (2007), distracting. The difficulties in justifying the cost and time involved in going through the process loop to correct inaccuracies and improve results have also been discussed. As expected, the survey of the literature showed that there is a variety of different methods which can be used to estimate costs. However, there is no consistency in the way they are categorised. Niazi et al (2006) describes product cost estimation techniques and classifies them in two main groups, namely Qualitative (Intuitive and Analogical techniques) and Quantitative (Analytical and Parametric techniques).

Cost modelling literature mainly refers to the manufacturing cost model itself, data input used and model outcome or output; however, there is limited published literature describing details in terms of the data collection process and data collection methods applied along the CMDP itself. At the most, the data types and some common sources of information are mentioned and somehow described. Wierda (1991), for instance, presents a method (Feature Costing) which aims to improve the data collection and identification task in the CMDP throughout the integration of CAD/CAM with cost information for cost estimation early in the design process via feature-based modelling.

DS most commonly mentioned in the literature include expert opinion, historical costing data and accounting reports, maintenance handbooks, and manual and computerised production systems (MRP, MRP II). Figure 5.1 shows the DS identified from the literature review, company visits and observations, semi-structured interviews and Questionnaires I and II.

In addition, little is told about the boundaries and scope definition that surrounds the development of the model in support of assumptions, levels of detail, accuracy, and model purpose. Samid (2000) ascertains that most cost estimates and cost computations are placed at the *'knowledge-edge zone'*. There are cases when there is no clear established procedure to arrive at a cost figure. It is, in most cases, a matter of professional, knowledge based and experiential insight.

In the cost estimating and modelling domain, those methods which propose an estimate where the reasoning for the solution is not apparent or intuitive fall into a category known as 'Black Box'. There are four methods identified from the semi-structured interviews on the *'Black Box'* classification, namely, Expert Judgement; Neural Networks; Fuzzy Logic and Parametric Methods. The reasoning within Expert Judgement is not apparent because the mechanism that creates the estimate is undertaken within the mind of the expert based on the expert's experience. Cost practitioners are continually applying logic, skill, common sense, experience and judgement as part of the process of generating cost models and estimates.

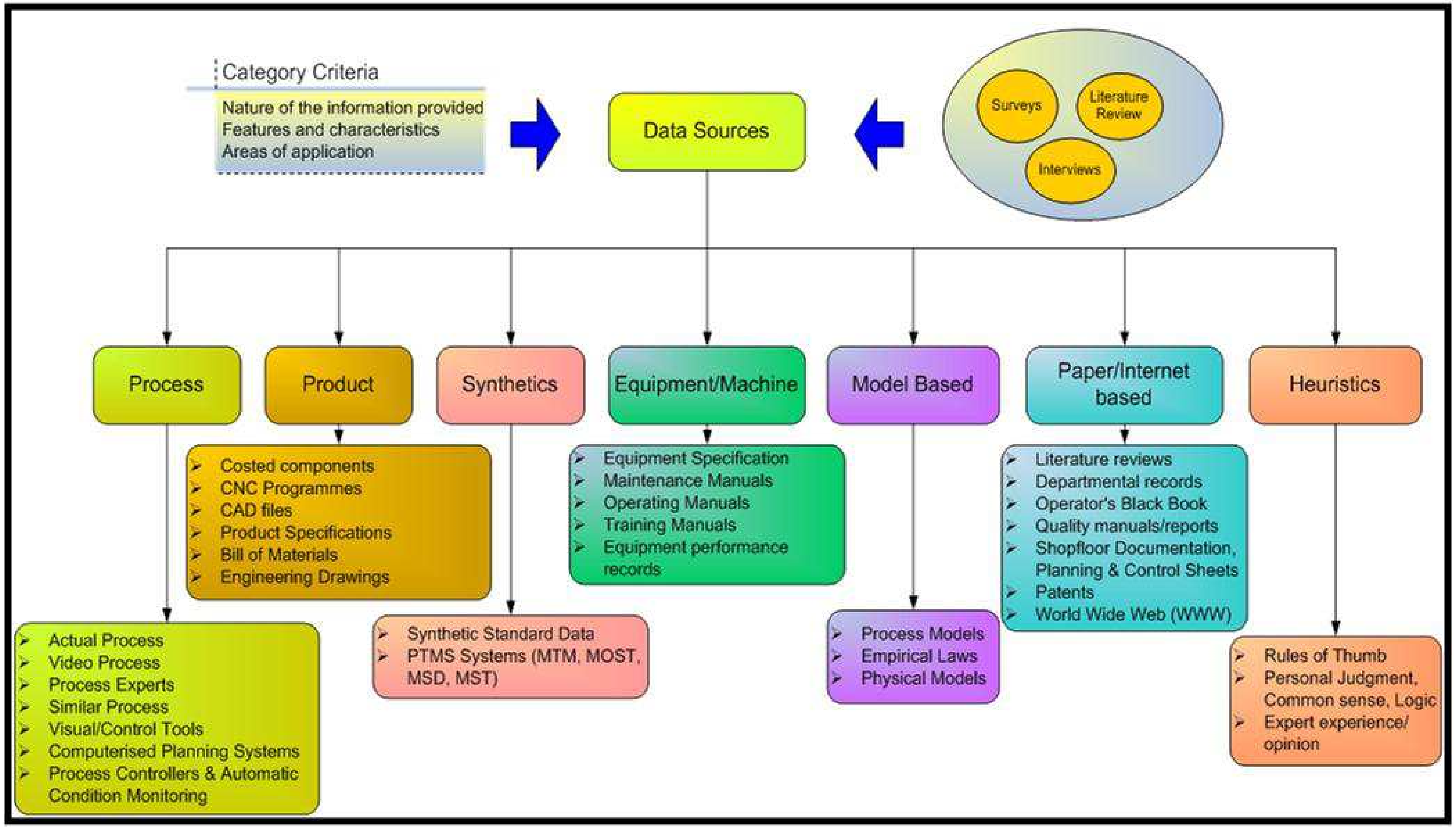


Figure 5.1 Detailed Taxonomy for Data Sources (Developed Work)

Research at Cranfield University (Rush and Roy 2001a and 2001b; Roy et al, 2001; Coley et al, 2007; Houseman et al, 2008) has found that the skills and knowledge required to produce cost models are complex and that the sources involved within the cost estimating environment are varied. The research points out the difficulties faced by non-cost professionals and specialists from different business functions (who ultimately use the outputs of the model) to understand how a final estimate is derived, and to visualise the fundamental reasons behind the several assumptions used throughout the process. Among the outcomes of the research, there is a proposed methodology to elicit cost estimating expert knowledge and also a study that looks at the relationship between design and cost estimating cognitive actions.

Neural Networks, Fuzzy Logic and Parametric methods are also 'Black Box' methods which are distinguished from Expert Judgement as the estimates are created based on statistical analysis of historical data. On the other hand, Knowledge-based systems; Case Based Reasoning; and Group Technology are all methods where the cost is estimated based on the new case's similarity to cases previously dealt with and where the methods propose a solution in a way that makes the reasoning for the outcome apparent.

Some authors propose some kind of criteria for the use of cost estimation methods based on stages of the PDP (Rush and Roy, 2000; Duverlie and Castelain, 1999). However, there is no research presented to support why the methods can only be applicable at the stages suggested. Regarding the selection of criteria for using certain data types and/or potential DC-TTMs in cost modelling (based for instance, on the availability of cost data or cost model characteristics) no research was found. In the same way, it seems that cost data availability or potential DC-TTMs do not seem to be limiting factors to be considered by the authors of journal papers and articles, who propose representations and make suggestions of when different methods are applicable.

In this sense, there seems to be a lack of research on the selection criteria and use of DC-TTMs to gather cost data and information for the development and validation of manufacturing cost models. Consensus tools and methods such as Delphi technique, Nominal Group technique, and AHP could offer great potential in the cost modelling and estimating arena to effectively elicit data and information other than cost data types (as for instance, on cost model requirements, potential DS and DC-TTMs) as it has been the case in areas such as Design for Manufacturability (DFM) (Ong et al, 2003), technical economical evaluation and environmental impacts assessment in the manufacturing industries (Qiang et al, 1991) and as tools for solving problems in health and medicine (Fink et al, 1984).

It was also observed that there is a tendency in the literature to use ***Methodology*** and ***Methods*** indistinctly. A ***Methodology*** is a sequence of tasks or activities which occur in sequence or in parallel. ***Methods*** are procedures used alone or in combination, to collect and analyse information in order to, as in the particular case of cost modelling, develop a model (Giarratano and Riley, 1998).

DC-TTMs used in cost modelling and estimation were identified from the literature review, semi-structured interviews and Questionnaire I, including the already mentioned Expert Judgement for manual analysis of records, files, documents and computer analysis of records; IDEF Models; Questionnaires and Interviews; Video recording and Film Analysis; Direct Process Observation; Activity Sampling and Time Study; Process Flow Diagrams and Outline Process Charts; PERT; Delphi Technique. However, there is no available research to backup why the methods can be used.

A comprehensive list of DC-TTMs is presented in Figure 5.2. The following section describes the results on the potential applicability of these and other techniques identified during the research for extracting cost data and information from different data sources and data types at the different stages of the PDP.

Limitations identified by the researcher which may affect the DC process and associated DS and DC-TTMs are listed in Table 5.1. This list is not exhaustive and is based on a combination of the literature on the topic and on the author's expertise and knowledge developed over the years while working in the cost modelling area. It has not yet been justified using other research methods such as surveys or interviews with expert in the CMD domain.

Method	Constraints
Expert Judgment	Susceptible to bias and unstructured Dependent on the experts Different experts use different mechanisms and approaches
Feature Costing	There is not an unique criteria or consensus as to what features are It requires large resources
Parametric	There is no criteria or consensus as to what parameters should be included Those parameters not included could become important at a later stage
Function Costing	Despite allowing to compare cost and functionality, does not generate accurate estimates
Group Technology	It requires some level of intuition to know the origin of the estimate It is not appropriate for innovative projects or solutions Susceptible to bias
Neural Network	Logic is not visible High level of complexity involved and subjective inputs Algorithms may be company specific and not be suitable for model development in general
Case-based Reasoning	It is not appropriate for innovative projects or solutions
Top Down	It provides little detail for justifying estimates It is less accurate than other methods
Bottom Up	Because it is based on detailed analysis and its estimates address low level tasks, it requires more estimation effort and development time compared to other methods It may be hard to build an accurate model to perform the estimate early in the lifecycle
Analogy	It based on actual project, process or product data and past experience, it is not always applicable as similar projects may not exist and historical data may not be accurate

Table 5.1 Possible Constraints affecting the Cost Data Collection Stage in the CMDP

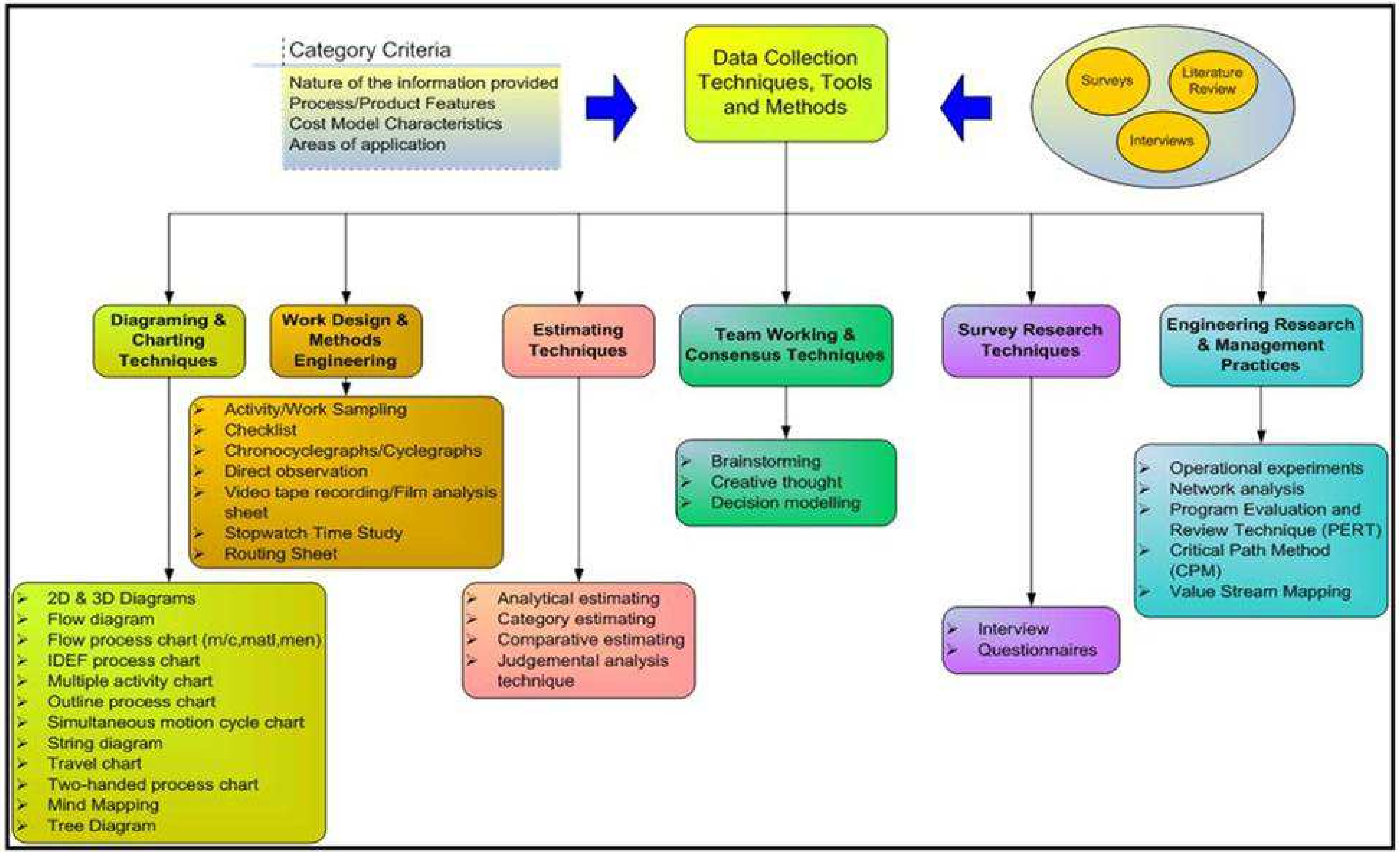


Figure 5.2 Detailed Taxonomy for Data Collection Techniques, Tools and Methods (Developed Work)

5.2.2 Questionnaire I and Interviews

Questionnaire I was designed and applied in order to support the Literature review and to identify cost modelling trends used in industry, identify how the CMP was conducted, possible gaps and needs for improving the CMDP. Three companies and twenty participants were involved. The response rate was 95%.

Questionnaire I included open questions to identify characteristics of the cost model and to collect information on the CMDP, model user and developer, manufacturing or business process costed or estimated using the model, data inputs and model outputs, function and application of the cost model between business and the estimating accuracy among others (Table 5.2).

AREAS	QUESTIONS
i. On the Cost Model:	1. What are the functions of the cost model? 2. Manufacturing or commercial processes that can be costed/estimated using the model 3. Data inputs and model outputs, including subjective data, non-subjective data and historical data 4. What is the estimating accuracy of the model?
ii. On the Model User/Developer:	1. Who uses the output from the model? 2. Who estimates costs using the model? 3. What expertise do they need to use the model?
iii. On Data Identification and Collection:	Do any problems arise when: 1. Gathering information? 2. Using raw data to obtain cost information? 3. Making use of cost information?
iv. On the Cost Model Development Process:	1. Describe the process and specify time and resources required to collect input data? 2. Describe the process and specify time and resources for developing the cost model? 3. What characteristics do you feel are important for cost models?

Table 5.2 Areas and Questions included in Questionnaire I

Appendix A2 includes a list of the models from the participant organisations and samples (extracts) of Questionnaire I for some models.

In order to ensure, maintain and protect the confidentiality of industrial collaborators and their businesses, the following measures were taken into account along the investigation data collection and subsequent data analysis:

- All of the identified information about models and projects that could make them identifiable has been omitted and codes have been used instead.
- The names of the interviewees and survey participants have been kept confidential.

- Information matching the companies and the models has been omitted because of the sensitivities around the confidentiality issues related to competitiveness, cost information and business strategy.
- Only information relevant to the research questions has been included and discussed.

This does not affect the conclusions and findings of the study. For the data analysis, information regarding the topics listed in Table 5.2 and particularly issues regarding the state of the cost model and current constraints and limitations will be discussed. The outcomes from the interviews include identifying the potential areas of concern and issues affecting the CMDP, especially those factors affecting the Data Collection Stage within the CMDP. These are presented in the form of a Cause and Effect diagram (Figure 5.3).

The range of models selected went from models in the early phases of development to mature models, for products at the PDP definition stage up to products already at the PDP production/commercial stage. Due to the commercial sensitivity involved, the exact model details could not be revealed; however, the methods and process whereby the models were developed as well as main model characteristics were established.

Some new information was collected on the problems associated with the CMDP. The identified causes for concerns and problems were collated and are presented in Appendix A3. The analysis of these issues for concern identified by the survey is presented in the Cause-Root Diagram of Figure 5.3, highlighted in red. Interestingly, most of the root causes previously identified in the literature consulted by the researcher (coloured in black on the Cause-Root Diagram in Figure 5.3) were also mentioned by the survey participants.

The above analysis (Figure 5.3) is an account of the interviewees' opinions and experiences on the issues surrounding the CMDP, especially those involving sources of information for the model, input data and the data collection tasks.

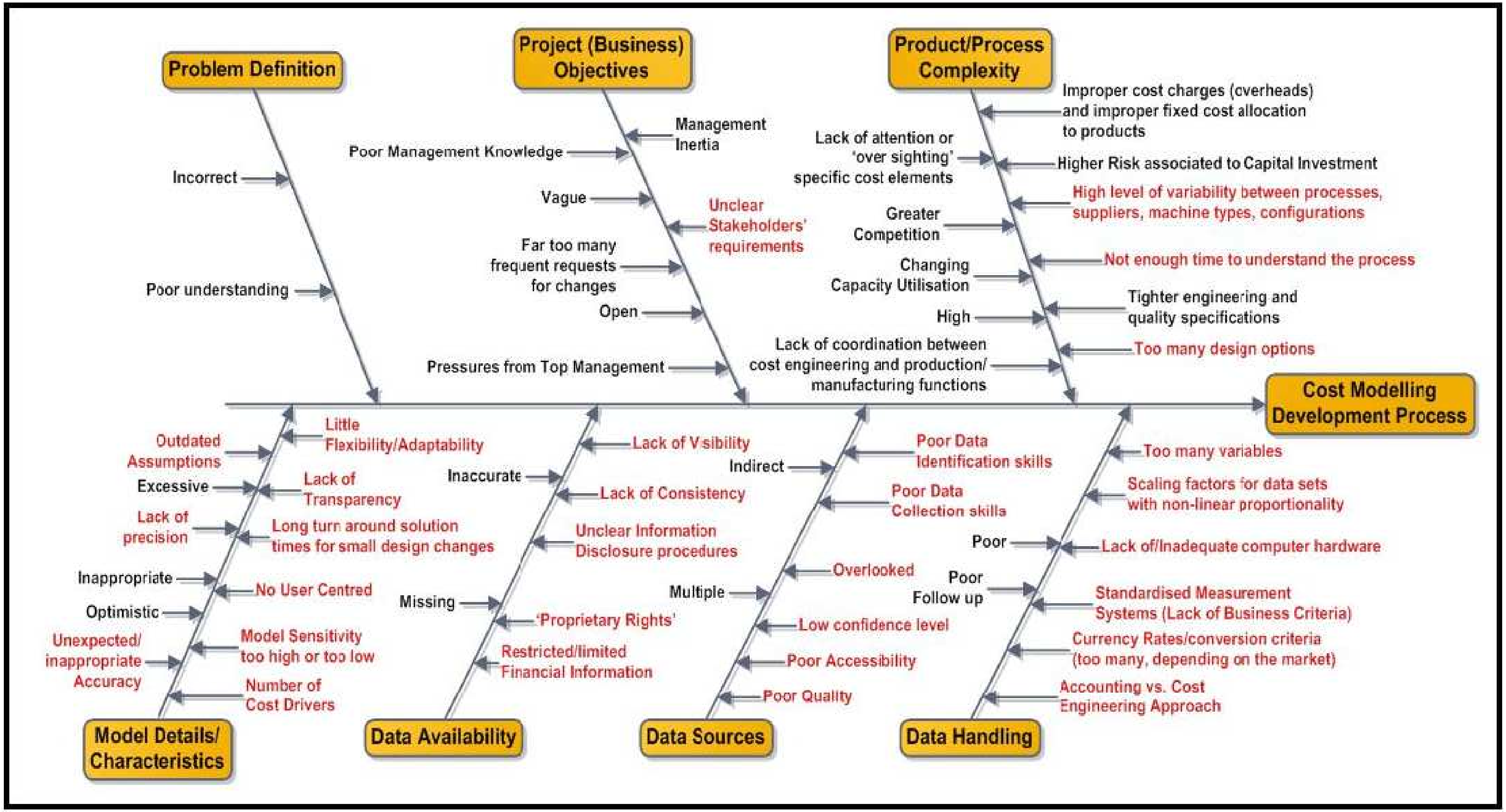


Figure 5.3 Fishbone Diagram listing the identified causes of concern in the Cost Modelling Process (Developed Work)

More than two and a half decades ago, Mathews (1983) collected his experience and observations on what he considered were the most common cost estimating problems. It is interesting to see that many of those concerns are still present today. Inadequate or insufficient data sources; lack of time and resources to build the model and prepare the estimate which leads to unrealistic outcomes outside acceptable ranges of errors; lack of coordination between cost engineering and production and manufacturing functions hence the cost model is built using outdated or incorrect data and information on capabilities, speeds, yields and costs. Improper cost charges, particularly overheads, and improper fixed cost allocation to products; lack of feedback; lack of attention or 'over sighting' specific cost elements that will be incurred in making the product which, despite looking irrelevant, can lead to significant error when failing to include their 'share' in the model CERs and cost calculations.

Optimistic cost modelling approach and poor model follow up, management and control along with Management Inertia to provide the required information on requirements and business objectives and to action improvements to support the cost modelling and estimation functions are all issues still affecting the CMDP. The above imposing set of problems have been identified and discussed and are part of the Cause and Effect Diagram in Figure 5.3.

Only by reviewing these problems and defining the most common difficulties, the solutions and changes required can begin to be approached, structured, planned and finally implemented.

This research investigation includes a new CMD Methodology which includes a Model Scoping Tool (MSF) to assists in defining the core characteristics of the model, identifying the purpose and features of the product/process involved and the potential sources of information and DC-TTMs in an attempt to solve some of this issues by facing them right at the model definition stage.

To this end, the cost model characteristics identified by Questionnaire I as the core elements to be considered when developing cost models include:

- As expected, cost model accuracy along with right information is at the top of the list as the most important characteristics.
- The cost model should be user friendly and user compatible. It should have visual transparency and mathematical traceability and be able to

explain cost break-down and outputs, in order to provide confidence on the model outputs.

- The information should be grouped in a rational, traceable and meaningful way, with the necessary information simplification and rationalisation. This means building technicality into model, yet keeping a good level of simplicity.
- It should have the ability to provide flexibility to the users of the output of the model and a quick response (speed with many iterations of design) to allow for fast modifications (model adaptability).
- Qualification and quantification are less of an issue. However, consistency is important as the model is often used as a comparison tool.
- It should have a clear purpose, in terms of the decisions to be made using the model, and also in terms of the requirements of the user of the model output. It is important to know the requirements from the final user of the model in order to produce the outputs that the user needs. To do so, it is also necessary to use input data that is realistically available.
- Another important characteristic would be sensitivity. This is to be able to advice the user about the range (+/-) the output covers. The output should not be a unique, single value. And the amount of information provided should be higher. The model should also allow conducting studies regarding the effect of changing any of the factors that affect the model output. This is recognising step changes that take place in cost estimation and which add costs.

5.3. Formulation Stage: Questionnaire II, Interviews and Focus Groups

5.3.1 Questionnaire II and Interviews

As previously described in Chapter 4, this is a closed question survey developed and applied in order to respond to the research questions for the Formulation Stage of the ESMM research methodology (Figure 4.1). The aim was to look into some elements in much more detail, focusing on:

- Types of Cost Models and range of tools, methods and techniques used for model development
- Cost Model Characteristics and Factors that influence the development of cost models as identified by the Literature Review and Questionnaire I
- Model Purpose and Business Objectives the model serves
- Data Sources and Data Collection Process in the development of cost models and possible relationships with the above elements

A total of 250 questionnaires were distributed. The response rate was of 18%. Questionnaire II was structured as follows:

- Questions 1 to 4: Company Profiling (Section 5.3.1.1)
- Questions 5 to 10: Cost Estimation and Modelling Functions (Section 5.3.1.2)
- Questions 11 to 24: Cost Model Characteristics, Data Sources and Data Collection Process (Section 5.3.1.3)

5.3.1.1 Company Profiling

The responses for the survey came mainly from the Aerospace sector with 71%, followed by Construction with 13%. Only 3% of the totals were responses from businesses in Electronics. Other sectors combined made up for 13% of responses; this included Automotive and Process (Gas and Oil Refining). Surprisingly, Software, which is an area where cost models and estimates are widely used, produced no response (0%).

Initially, the project was limited to the Aerospace Manufacturing sector. Later on, in an ambitious attempt to broaden the scope of the project other company sectors where approached. It seems that because of the strategic and confidential nature surrounding the cost modelling and estimating functions, the level of response from other sectors was very limited. These companies were approached using the online survey mode and the companies targeted were obtained from company directories from the organisations and professional institutions listed in Chapter 4. These were mainly companies in the Construction, Software, Electronics, and Defence sectors. Other sectors included Automotive and Process industries. All these industries are known for using cost models and estimates along their product development processes.

For Aerospace companies, on the other hand, the mail questionnaire and face to face interview survey modes were applied. It seems that these survey methods are more effective when dealing with issues of high confidentiality and strategic nature. Another possible reason for this may be the differences on how cost modelling and estimation is performed at those organisations and for which the scope and outcomes from this study may have been seen as irrelevant or of no application.

The main business activities carried out by the participant organisations were the design and manufacturing of complete products (53%) including, for example, whole aircrafts. These are typically OEMs. This category is followed by the manufacture and design of parts, sub-systems and sub-assemblies (42%) which include producers of avionic systems and brakes, for instance. Only 6% of participant companies are either designers of whole products only (no manufacturers) or designers of components only (no manufacturers). Because of the nature of these products, they are mainly manufactured in what qualifies as Low Volume manufacturing (71%).

In terms of their production processes, just over a half of these companies (55%) move their products in batches along the production process. A total of 23% work in projects and 16% said they use continuous flow line. This last trend is becoming increasingly common at the moment, with Project/One Off, Batch Production companies and their suppliers moving towards Low/High Volume, Process Flow Line manufacturing. This is particularly the case of Aerospace businesses trying to comply with market demands.

Appendix B2 Survey Questionnaire II – Company Profiling (Question 1 to Question 4), contains graphical representations (Figures B2.1 to B2.4) produced for the above analysis.

5.3.1.2 Cost Engineering and Estimating Functions

Participant companies will carry out exercises to develop models and estimates for all three major resources, namely Process Costs (36%), Product Costs (35%) and Process Times (29%) for different functions within the organisation. There is no marked predilection for developing models for any particular resource, and estimates are spreadly produced for all three resources.

Participant companies seem to develop a whole range of cost models and estimates, from the Conceptual (Order of Magnitude) up to the Prototype (Detailed) Estimate. Other models were also identified (accounting for just 7%); these included Non-

Recurring Engineering (NREs for one-time cost of researching, developing, designing, and testing) and Non-Recurring Cost (NRCs for Tooling) models, Commercial Supplier Negotiations and Cost per unit of existing component in the Aerospace Industry and all of the AACEI Classes of Estimate in Construction/Capital Project estimating.

All three types of models and estimates are produced at the surveyed companies: Conceptual Estimates/Order of Magnitude (34%), Preliminary Estimates (34%) and Prototype/Detailed Estimates (25%). This shows that cost models are used all along the products lifecycles at the participant companies, particularly at the very first stages of their product development process.

Procurement (39%) seems to be the business unit predominantly responsible for the development of cost models among most of the respondents, followed by Manufacturing (23%). From a total of 23% of respondents that stated that their cost models were principally developed by other functions, more than 40% of the respondents indicated that it is Cost Engineering (45%) the entity responsible for developing the models. Value Improvement (11%); Financial Management (11%); Commercial (11%); Tendering (11%) and Engineering (11%) were also mentioned. The Design function, with only 10%, seems to be the less likely ‘location’ within the business in which the responsibility of producing the cost models will rest.

Matthews (1983) suggests that estimates (as an independent and realistic prediction of what the cost to make a product will be) are greatly affected by the location and rank in the management hierarchy of the estimating function. A similar effect will be also observed for cost modelling.

As discussed in Chapter 1, if the decisions made at the definition stage of the product development process are not supported by the require cost information demonstrating the effects of those design decisions over the total product cost, designers cannot make the necessary adjustments or modifications to make the product more cost effective and competitive. Furthermore, if the feedback on those effects has a long lead time, then the changes may not be feasible. The Design Division within organisations seems to be a static source of information disconnected from the cost modelling and estimating function rather than a dynamic proactive source of feedback according to the opinion expressed during the interviews. This may add to the constraints in the data collection task and long lead times during the cost modelling development process.

Regarding the preparation of the cost estimates, results indicate that Procurements is the function primarily responsible for this task (52%). Only 13% of respondents indicated that Manufacturing was responsible for producing the final estimates and Design was last with only 3%. A 26% of respondents specified other areas as the main function responsible in generating final estimates, including Cost Estimating and Senior Manufacturing Management, Financial Management, Value Improvement and Commercial. It has to be mentioned that, in most cases (77% of the responses), the cost model and the final estimate are both prepared by the same function.

This may be the common case for big organisation where the cost modelling and estimating function are integrated under the same unit. However, the level of product complexity and the levels of technological and engineering demands for its production will ultimately decide where and at what level of management the generation of models and estimates will take place (Hollmann, 2007).

The more complex and difficult the cost estimating task, the higher its rank within the organisation. Furthermore, the more likely it is to be used in the management decision making of business objectives such as technology changes and new product introduction.

This will have a drastic effect on the cost modelling process, particularly, the data identification and collection stages as the availability of cost data and information is insufficient or difficult to obtain in most cases. The different format (sometimes irreconcilable) in which the information is presented at different management levels and business units will also affect these and other tasks in the CMDP such as data analysis and data management.

In SMEs where there is no specific function responsible for producing the cost model and the final estimate, the process owner or operator makes the best possible cost estimate for the process or product under consideration. In some cases, different departments prepare their own cost models and estimates, such as labour costs and tooling costs models prepared by Production; material and purchased-components costs by Purchasing; engineering costs by Engineering, and so on. Finally, the overhead rates, provided by Accounting, will be applied. Then one department, usually Accounting, will add everything together to obtain the final product cost. This may make difficult to trace back information and assumptions made; check for accuracy and re-visit data sources.

In some other cases, cost modelling and estimating are performed by one department, such as Production Management or Cost Accounting, which carry out these tasks as part of their other work. Data is collected from other departments and business units including Purchasing and Engineering, for example.

As said earlier, greater product complexity, higher engineering and technology involved for product manufacture as well as bigger company size all call for a separate and dedicated cost engineering and estimating function to provide independent and realistic prediction of product costs (Matthews, 1983). The fact that 90% of the respondents stated that at their organisation, at least 10 hours or more per week are spent in cost modelling and estimating tasks suggests that these are considered part of their business activities or practices at least at some extent.

A total of 45% of respondents indicated that their organisations spend 30 hours or more per week in modelling and estimating, which suggests that because of their product and processes characteristics, any change or miscalculation may have a significant impact on the associated costs; therefore, they require accurate cost models and quality estimates. With a more complex product or process, as the ones generally found in the Aerospace industries, cost modelling and estimating is more elaborate. Hence, it is easier to make mistakes and the errors are usually more expensive and obvious.

Follow up interviews indicated that, most of this time is dedicated to the collection of up to date data and information on cost parameters from Production, Purchasing, Engineering, Manufacturing and Accounting functions by the division or business unit with appointed responsibility for developing the cost model and final estimate. Because of this, for big players in the Aerospace industry, it seems to be common practice to have dedicated staff working in cost engineering tasks. Only 6% of respondents said that they had only one estimator. A total of 23% of the respondents have 30 estimators or more. The majority (29%) indicated that they have between 2 and 10 estimators. A total of 23% responses corresponded to 20 to 30 estimators.

In some cases, cost modelling is not the only job the cost practitioner has. Actually, it may be part of his/her workload. Nonetheless, the significant effect of accurate cost models and quality estimates on the business operating performance implies that this task should not be handled as a part-time responsibility. Furthermore, top management should recognise and accept the importance of accurate cost models and good estimates as soon as the company's size and product and process characteristics indicate the need for such an action.

Appendix B3. Survey Questionnaire II - Cost Engineering and Estimating Functions (Question 5 to Question 10), contains graphical representations (Figures B3.1 to B3.6) produced for the above analysis.

5.3.1.3 Cost Model Characteristics, DS and DC-TTMs

In Chapter 2 the resources that can be costed or estimated using cost models were described. As shown in Figure 5.4, Material (23%), Direct Labour (17%) and Process Time (17%) were indicated as the main resources estimated by the respondents. They were followed by Capital Asset (13%), Indirect Labour (12%) and Manning Levels (10%). Other costs identified (which combined account for 7% of responses) were Purchases, Consumables and Fixtures; Tooling, Replace/Fix ratio and Profit Margin; WIP, Scrap, Yield; Elapsed Time; Suppliers' Price; Development Cost of the Total Programme; Fixed and Variable costs (not elsewhere specified); Head Office Cost; Estimate total Life Cycle costs for major Air Force Weapon Systems and Automated Information Systems (AIS).

This suggests that there is a range of cost resources that can be estimated and modelled: from the basic product cost resources such as material, labour and overheads up to Development Cost of the Total Programme, Total Life Cycle costs and Head Office Cost. As discussed before, the selection of the type of resource to be costed and, therefore, the model developed for it will depend not only on the product/process complexity, features and activities, but also on the model purpose and its characteristics, including business objectives and levels.

The more the company's business objectives are sensitive to the effect of the model outputs on the final estimate, the higher the demands on refined procedures, higher orders of estimating accuracy, better controls over performance and, ultimately, higher the position of the cost engineering and estimating function within the company organisation. High level models for strategic purposes may be developed by top management functions such as the model for Development Cost of the Total Programme, for instance. They will require the input from Low Level Cost models developed by Production or Engineering including material cost, tooling and testing cost models.

With regards to the type of cost elements used for building cost models, Figure 5.5 shows that all three types described in Chapter 3 are used for the participants when developing the cost models for the resources they cost and estimate. All three cost elements can be used at any one time when producing a cost model. Respondents indicated that they include Product Features (31% of responses); Process Features (28%) and Process Activities (29%) as part of their models and estimates.

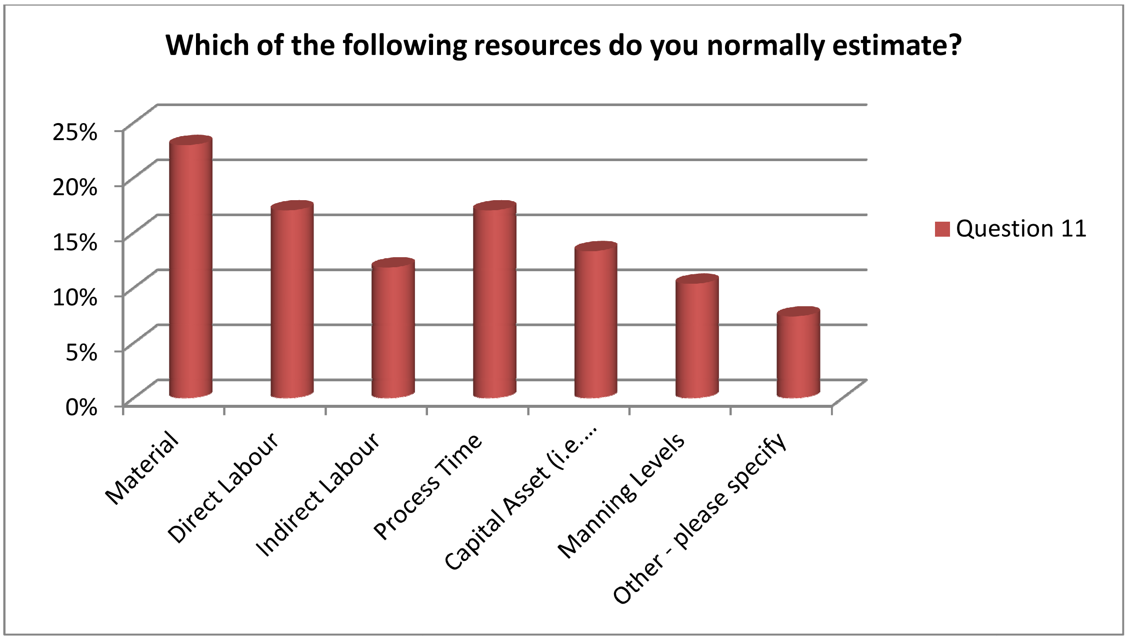


Figure 5.4 Cost Resources normally estimated/costed

As per the number of these variables, only 68% of the respondents provided an answer. The respondents indicated that the number of variables is established by the design; hence, it can be assumed that the experience and skills of the cost modeller and estimator will be the most important factor when selecting the variables, data to be collected and methods to be used. Consequently, the right set of data collection and identification skills and resources; namely, data sources and data collection MTTs it is crucial in the CMP. The responses are listed in Tables 5.3 and 5.4, respectively.

Number of Variables	Responses
10	13%
15	4%
20	9%
40	4%
100	4%
150	4%
200	4%

Table 5.3 Maximum number of Variables

Rather than providing a number or a range for the maximum number of variables, some of the respondents provided the following answers instead (Table 5.4):

Number of Variables	Responses
Depends on size/complexity of system being estimated	4%
Depends upon commodity	4%
As many as possible/available or as many as the process/design allows	19%
Depends on the model characteristics	4%
Depends on information/data available	19%
Around 6: Type of component; material; complexity factor; material weight; size factor; subjective factor	4%
Depends upon the production volumes	4%

Table 5.4 Comments on the Maximum Number of Variables

The level of detail required for the cost model and other model and process/product characteristics will determine their type, number and their level. Among some other cost elements or variables identified, the following were also mentioned: Batch Quantity; Total Production Quantity; Cost rates as additional process features. As indicated by one of the respondents, for a Total Programme Development, cost elements may include: Technology, Tooling, Product Testing Type, Cost of Testing Equipment, Prototypes, Servicing, Weight, Production Rate, Volume and Size. For Facilities (as a product), variables vary depending upon facility type. Common variables are type, size, number of bidders, location, and distance from utilities, among others. As expected, the type and level of the cost elements will depend on the industry as well as on other factors as already discussed in Chapter 3.

Sometimes, it is necessary to go to the next level down in the product breakdown structure in order to gather the required cost data and information for the element above (Bottom Up Approach). Hence, to work out the total product cost of a wing box, it is necessary to gather the cost elements associated with the components and subassemblies involved in the manufacture of the final product. This implies identifying and collecting information on the product and process features and process activities for producing those components; in addition to building cost models of their respective cost drivers or resources whose outputs will be inputs in the final model for the total product cost of the wing box. Any gap in the cost model developing process of those models or individual model errors will have an impact on the final model.

In other cases, an estimate of the total cost of a product can be made available. In this case, the purpose of the model, for example, will be to comply with the business objective of determining a Cost/Weight Trade-off, to justify a strategic company's move involving the use of a new light-weight alloy to manufacture the part in question, in light of tightening of emissions regulations and volatile fuel prices.

The cost elements at their respective higher levels will be use to feed high level parametric models, analogies, or cost estimating relationships (CERs) to produce an overall model output or estimate using the new material. Then the contribution of the different costs incurred to produce the final product will be calculated down the layers of the product breakdown structure (Top Down Approach). This time, the sources of data and the information (historical data) required may be already available, and the level of judgement subjectivity as well as the experience of the cost modeller and estimator may be the deciding elements on the accuracy and validity of the final outcome and the main sources of possible errors.

The way in which the respondents mainly obtain their cost and times estimates is through the generation of cost models (48%), as shown in Figure 5.6, followed by detailed cost estimates (39%).

Some respondents use either cost models (32%) or detailed estimates (16%), while the majority use both approaches (52%). As discussed before, the outputs from cost models can be used as inputs for an estimate. If this is the case and based on those results, then it seems that, in most cases, the person who builds the model also prepares the estimate. The reason why in the responses indicating either one or the other is because a) only one approach is used for decision making or b) the preparation of the model or estimate is outside the responsibilities of the individual answering the questionnaire, and therefore is not applicable.

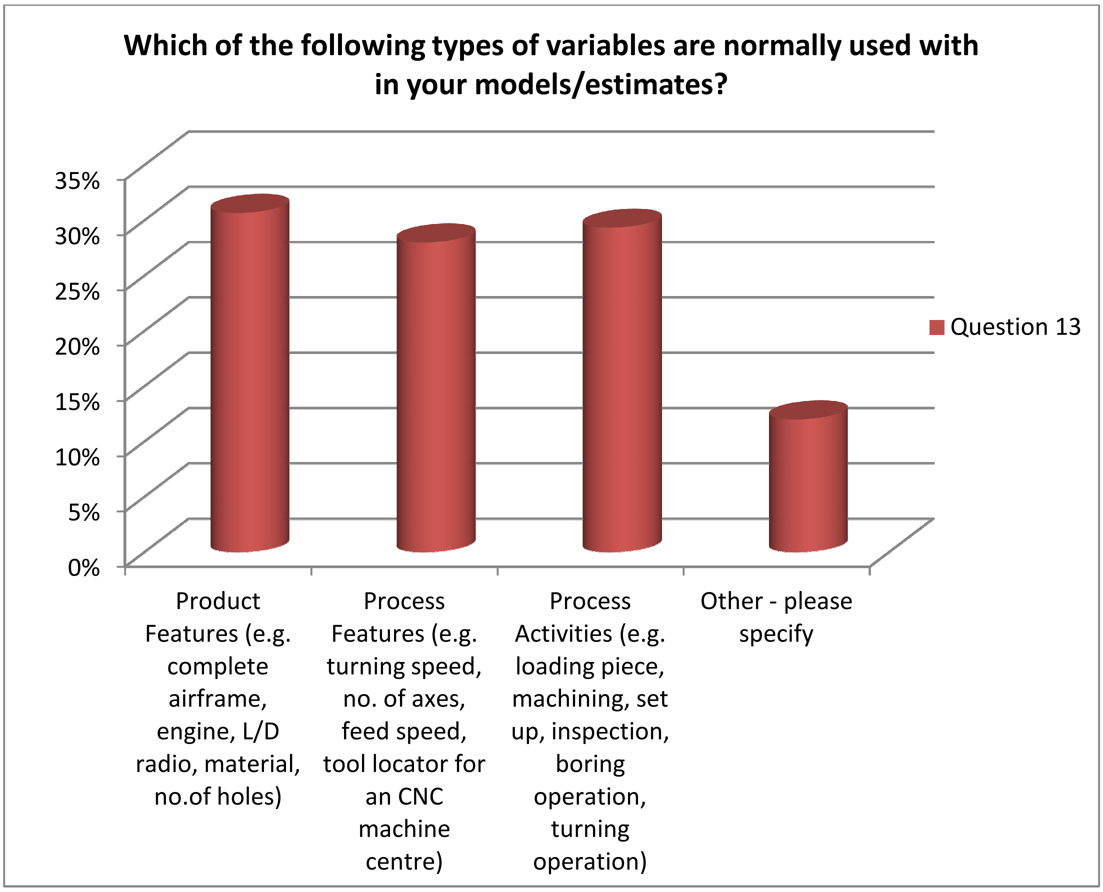


Figure 5.5 Cost Elements or Variables used in cost models and estimates

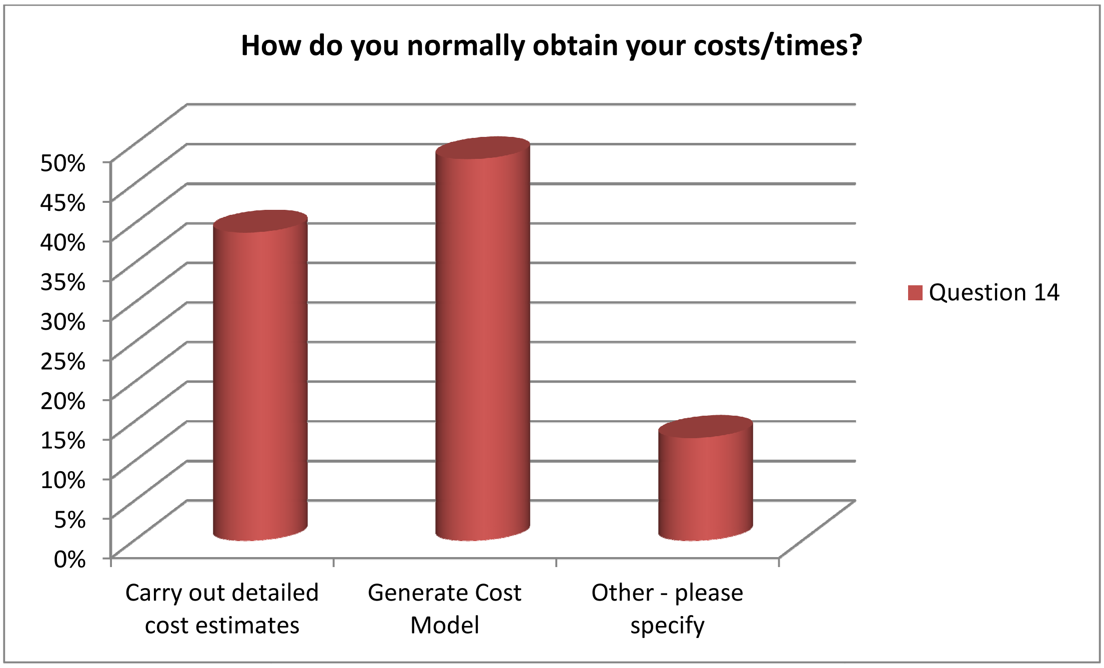


Figure 5.6 Approaches to obtain cost or time estimates

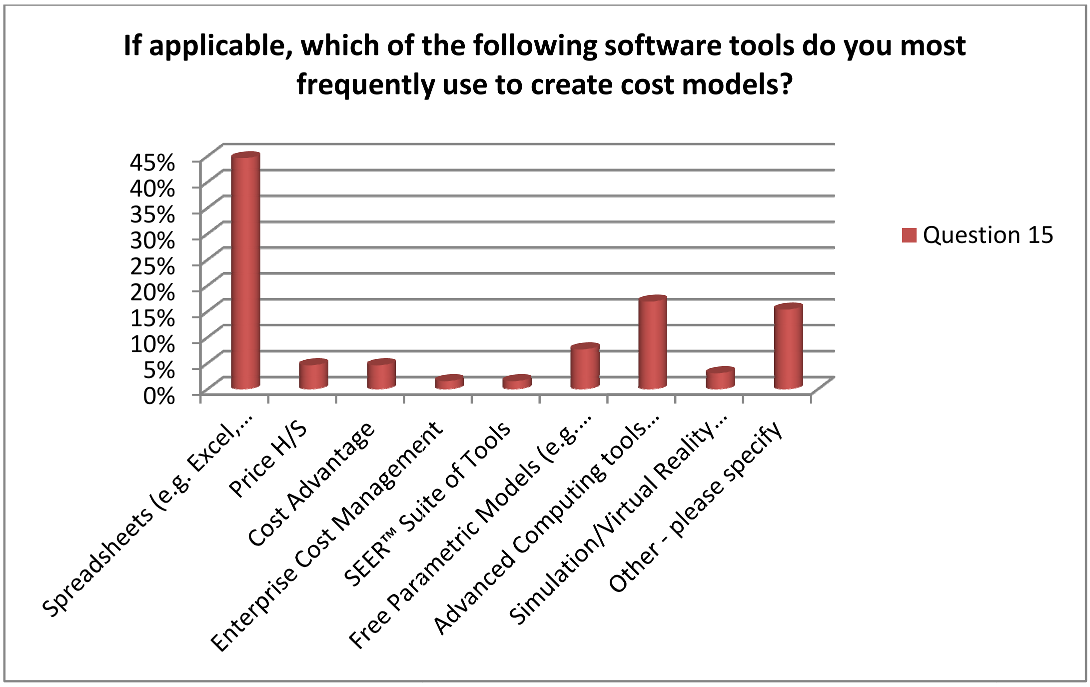


Figure 5.7 Software tools used in cost modelling and estimating

According to the respondents (during the follow up interviews), these models and estimates can be high and/or low level models and/or estimates, and Top-Down and Bottom-Up are the approaches mainly used for building them. Data collection tools employed for this purpose included detailed breakdown structure, work/method study, synthetics and actual times.

For the majority of the respondents the preferred software tool for developing models is Spreadsheets (45%) as shown in Figure 5.7. Reasons given included:

- Option of customising the model and flexibility
- Skills levels required were already available within the company
- Transparency in terms of model assumptions, rules and logic
- Protection of the know-how built inside the company

The downside of using Spreadsheet, however, it is that the person who builds the model may do it as a part-time job and the maintenance and management of the model becomes second place or last as management may not see it as a value added activity or top priority. The worst case scenario is that the model builder may leave. Therefore, there is a risk of the model going outdated or obsolete.

Spreadsheets are followed by Advanced Computing Tools such as Artificial Intelligence (AI), Expert Systems and Knowledge based tools with 17% of the respondents indicating that they use them. A total of 15% the participants use other tools including Statistica, ACEIT, Arisca – Predict, MS Access Database and CAPPE.

A range of commercially available and proprietary software solutions are available to the cost modelling and estimating community. These can provide information on the machine cycle times, total throughput times, manning levels, bottlenecks. Interestingly, only 5% of the respondents use Price H/S; 5% use Cost Advantage; Enterprise Cost Management is used by only 2% of the participants and so is the SEER™ Suite of Tools.

A total of 8% of the participants use Free Parametric Models and only 3% apply Simulation or Virtual Reality Tools (such as SIMUL8, WITNESS and Techmatics). A possible explanation of this trend is that commercially available software and proprietary solutions may still be considered 'Black Boxes'. Despite their inherent and immediate benefits such as allowing visualising and/or quantifying the results of different options or scenarios and demonstrating the implications of different business decisions on ad-hoc basis; if the wrong assumptions are made with respect to the real scenario, the magnitude of the error may have exponentially increasing effects on the accuracy of the cost model outcome and final estimate. In addition, the deployment costs (set-up, training, license costs) against the perceived benefits may not yet justify the investment. As discussed previously, management may not see cost engineering and estimating as a priority which may add to the situation.

The tools described are used to produce different types of models (Figure 5.8). Statistical Models (counting in Regression Analysis, Time Series and Causal Cost Models) are the type of models developed by 48% of the respondents. A total of 24% of the participants indicated that they develop Knowledge based models. Risk Analysis using Monte Carlo Simulation is conducted by 19% and 9% stated that they also use other tools.

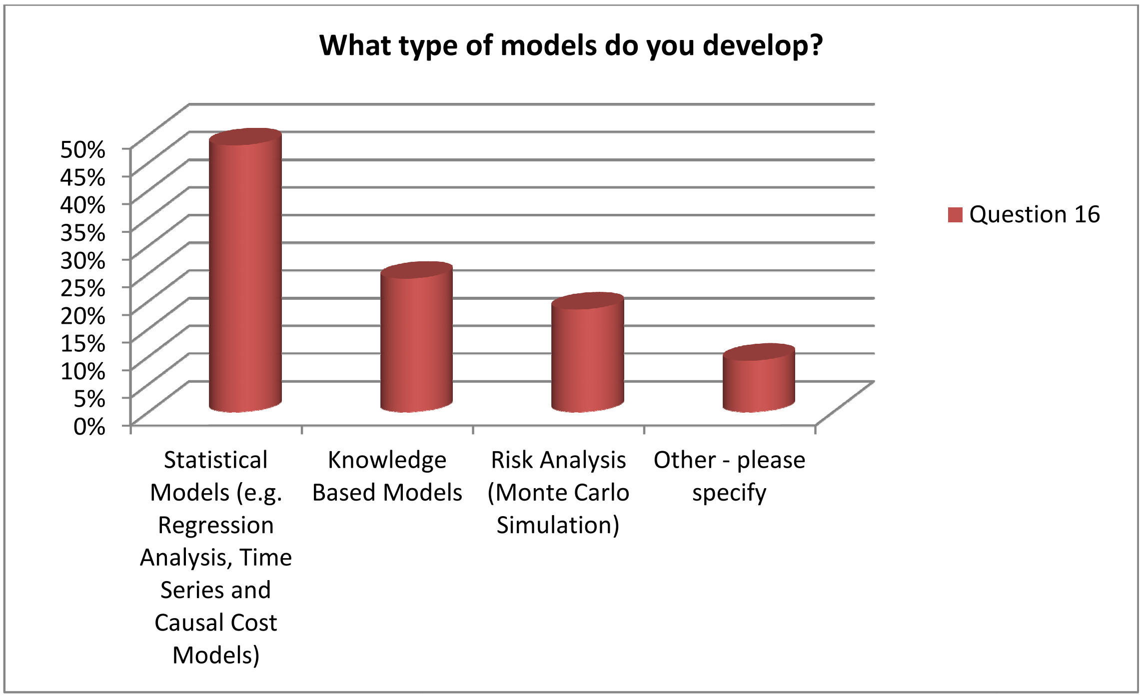


Figure 5.8 Type of models developed

Regarding data collection tools, techniques and methods the participants use when developing their cost models (Question 17), the following list summarises the ones identified:

- Manual Extraction/Manual Data Collection entered in Excel from actual project data.
- Rule of Thumb; Guesstimation; Heuristic Rules.
- Observations, mainly observation whilst at suppliers; observation of Experts and Direct Observation of process operation's demonstrations, Company Visits and Supplier Visits; Feedback; Process and Product Experts Interviews (external and internal); Interviews to Manufacturers and Suppliers.
- Internet searches/Technical Searches/Databases searches/Literature searches, reviews.
- Questionnaires; Checklists; Drawings; Schemes; Product Life Cycle Mapping; Process Mapping; Process Flowchart; Histograms/Pie Charts; Tree Structure Mapping; Gantt Chart.

- Expert Opinion, Judgement and Intuition; Experience of cost estimator or modeller; Expertise and skills (Senior Cost Engineers); Brainstorming (Cross functional).
- Time Study (Stopwatch), Video Recording and Photographs; direct work measurement, lean manufacturing workshops at suppliers.
- Process comparison; Analogical estimating.
- Job cards, Bar Coding, MOST, Methods Study, PMTS (Predetermined Time and Motion Study).
- SWORD Design Constraints.
- Data Mining when using Internet.
- Presentations from partner companies in the project; Forecasting for cost drivers' identification.
- Simulation and Process Models.
- Supplier Pricing Analysis.
- In the process industry, particularly Gas and Oil, formalised data collection process and formats are also in place for projects. There is an industry normalised data sharing IPA (Important Plant Areas) Agreement and IPA database.
- It was reported that, in some industries, such as the US Aerospace Military (Air Force) and Department of Defence, there are specific cost data collection formats and regulations for large contracts for major systems and products. These formats are known as Standard Data Reporting Systems, such as the DoD 5000.4-M-1 Contractor Cost Data Reporting (CCDR) Manual (1999) for DoD organisations and defence contractors. The CCDR aims to ensure that data made available to cost estimators is both accurate and consistent. Other systems include the Defense Contractors' Planning Report (DCPR) used for evaluation of the economic impact of procurement decisions and for close control of development and production costs and the Cost and Software Data Reporting (CSDR) to support the collection of cost and software resource data on individual contracts for those contracts with software requirements. Also, raw data is collected directly from Industry.

As for the data sources identified by the respondents (cost estimators, cost engineers, process and model owners) in Question 18, they include:

- Expertise and Experience: Own expertise; Knowledge of cost estimator; Experiences of Cost Engineers; Engineering expertise and knowledge; Process Expert knowledge; Expert Opinion from process and model owners.
- Legacy databases; In house product/process databases; commercially available databases (Cost Advantage), MS-Access; Industry databases, Government databases; SAP (System Application and Products) centralised system/database for integrating business applications; Planning Systems Databases and Mainframe Systems (CAPS Systems); (Internal) Financial Systems; Database of previous models/projects (comparison and analogy).
- Statistical databases (global) used in the Automotive Industry include OECD (Organisation for Economic Cooperation and Development); ILO (International Labour Organisation); NSO (National Statistics Office); Experian/D&B/Bureau van Dijk; London Metal Exchange (LME).
- For Capital Projects, Facilities and Construction Industry in general Data Means, RSMeans (commercial cost data); and Richardson Process Plant Construction Cost Estimating Standards (PPCES) are sources of information on cost estimating standards for Chemical Plants, Manufacturing Facilities, Solids Processing, Water Treatment Plants and General Construction.
- Industry gathered data; External data; Suppliers in the Motor Trade Industry, metal factories and manufacturers of components; material suppliers and equipment manufacturers; Trade shows.
- In house Engineering and Process specifications; Company Specifications and Manuals JES/JDS/MSRR/RPS; Company and Industry Standards and Regulations; Technical Publications; documental process descriptions, Quality manuals; Guidelines Documentation, Code of Practice, Computer Aided Design (CAD) Drawings; Commercial Agreements with Project Partners (External); Inventory documents/Machine specifications documentation, Books, Drawings, Journal/Research Papers; Various trade publications (P&RW, EPN, RP).
- Rule of thumb.

- Questionnaires; Checklists; Drawings; Schemes; Product Life Cycle Mapping; Process Mapping; Process Flowchart; Histograms/Pie Charts; Tree Structure Mapping; Interview; Gantt Chart.
- Stopwatch; PMTS, direct work measurement, method study/lean manufacturing workshops at suppliers; Synthetic Time Standards.
- Word of Mouth / Experience/Expertise / Process & product experts (Suppliers) / Machine Operators.
- Process and Simulation models.
- Actual process, similar processes (metal assembled wings), Manufacturing Plans.
- Shopfloor: Job Cards, Route cards, Bar coding, MOST, Time Study (Stop Watch), Methods Study, Planning tools (Ceqel/PEGS).
- Direct work measurement, method study and lean manufacturing workshops at suppliers.
- Similar past processes and programs/Previous projects/Case Studies/Recent Detailed Cost Estimates/Historical Data on assembly processes and Previous Models historical data.
- Company Cost Ledgers/Actual Labour Cost/Actual Contracts with sub contractors/Vendors.
- Cross functional team of process experts
- Technical Searches on Internet Databases; and Government Websites (UK and USA); online virtual libraries from Trade Associations, Professional Institutions, Academic Organisations, Industry Societies and Chambers of Commerce. Government Agencies such as the National Aeronautics and Space Administration (NASA).

One particular online data source actively visited during the course of this investigation was online professional forums and SIGs. These are discussion groups were their members post enquiries or comments on particular topics. The two forums visited were The AACEI Cost Estimating Committee and The Cost Engineering Committee Forums. These forums in particular require a user account, are bound by netiquette rules, have a moderator and are for exclusive use of AACEI members (registration is required). Among the topics discussed members examine, debate and provide feedback and amendments on Recommended Practices for public review; ask questions about sources of information for cost elements and resources for estimates such as Labour rates at different locations and for a diversity of projects; escalation indices; historical cost databases, books and references; estimates assumptions and classification; industry trends and best practice, including the AACEI Total Cost Management Framework (2002). A copy of the Questionnaire II was posted on the Forums and 19% of the replies received came from members of the Committees.

It has to be mentioned that the respondents identified some DC-TTMs as data sources as well. In other words, they are considered both a data collection tool and a source of data. As discussed in Chapter 3, sometimes a DC-TTM for primary data becomes a data source for secondary data collection. This is the case of PMTS, Time Study, Process Flow Charts and Process Models. It seems then that another possible criterion to be included in the classification of DC-TTMs is the type of source the information is to be collected from using the DC-TTMs, namely primary data source (direct first hand information) or secondary data source (information transmitted –second hand- through another source). No mention of ERP (Enterprise Resource Planning) systems was made.

After identifying the background information and establishing some of the characteristics of the models, the participants were asked about the factors influencing the development of the cost models and estimates they produced (Figure 5.9); the lead times associated with the different steps of the process (Figure 5.10); the end use of the models after development (Figure 5.11); the levels in the decision making process the output of the models are used at (Figure 5.12) and the importance of risk considerations as part of the CMDP (Figure 5.13).

When considering the different factors listed in Figure 5.10 and their importance at the time of generating a cost model or estimate, the three most important factors, according to the survey participants, were the ***Purpose of the cost model or estimate, Availability of Cost Data and Estimator's expertise and skills*** all with a total of 71% each. Fifty two percent (52%) of the respondents considered the ***Time available to generate the model or estimate*** as another factor within this category.

The next category of factors, in terms of significance as perceived by the survey respondents (namely, Important factors), includes ***Time available to collect data; Time available to input data and Data Collection tools and techniques available***. Again, ***Time available to generate the model or estimate*** comes second with 45% after the highest scoring factors in this category (with 58% each).

Finally, the factors considered ‘important to some extent’, with the highest scores within this category (29%) were ***Estimating Accuracy*** and ***Level of detail/type of estimate***. A small number of respondents were of the opinion that ***Data Collection tools and techniques available*** are not important factors when generating cost models (3%).

To summarise, as per the survey’s responses received, ***Purpose of the cost model or estimate, Availability of Cost Data and Estimator’s expertise and skills*** are considered the most important factors for success in the model development process. The ***time available to (i) collect data; (ii) input data; and (iii) generate the model or estimate*** follow next, along with ***the suitable Data Collection tools and techniques,*** as part of the success factors. It makes sense to think that, if all of the above factors are in place and have been adequately defined, planned and implemented, then the ***Estimating Accuracy*** and ***Level of detail/type of estimate*** should come next, not only as important factors but also as a result of having in place a methodology or approach which will ensure all of the above elements have been taken into account when planning the development of a cost model. These factors were also identified in Questionnaire I and discussed in previous sections.

In reality, poor communication and the need to re-visit sources of data and information along with the limited availability of people are constraints in the CMDP which need to be addressed.

The MSF proposed as part of the CMD Methodology developed during this research investigation aims to assists in defining those important factors and overcome the above limitations.

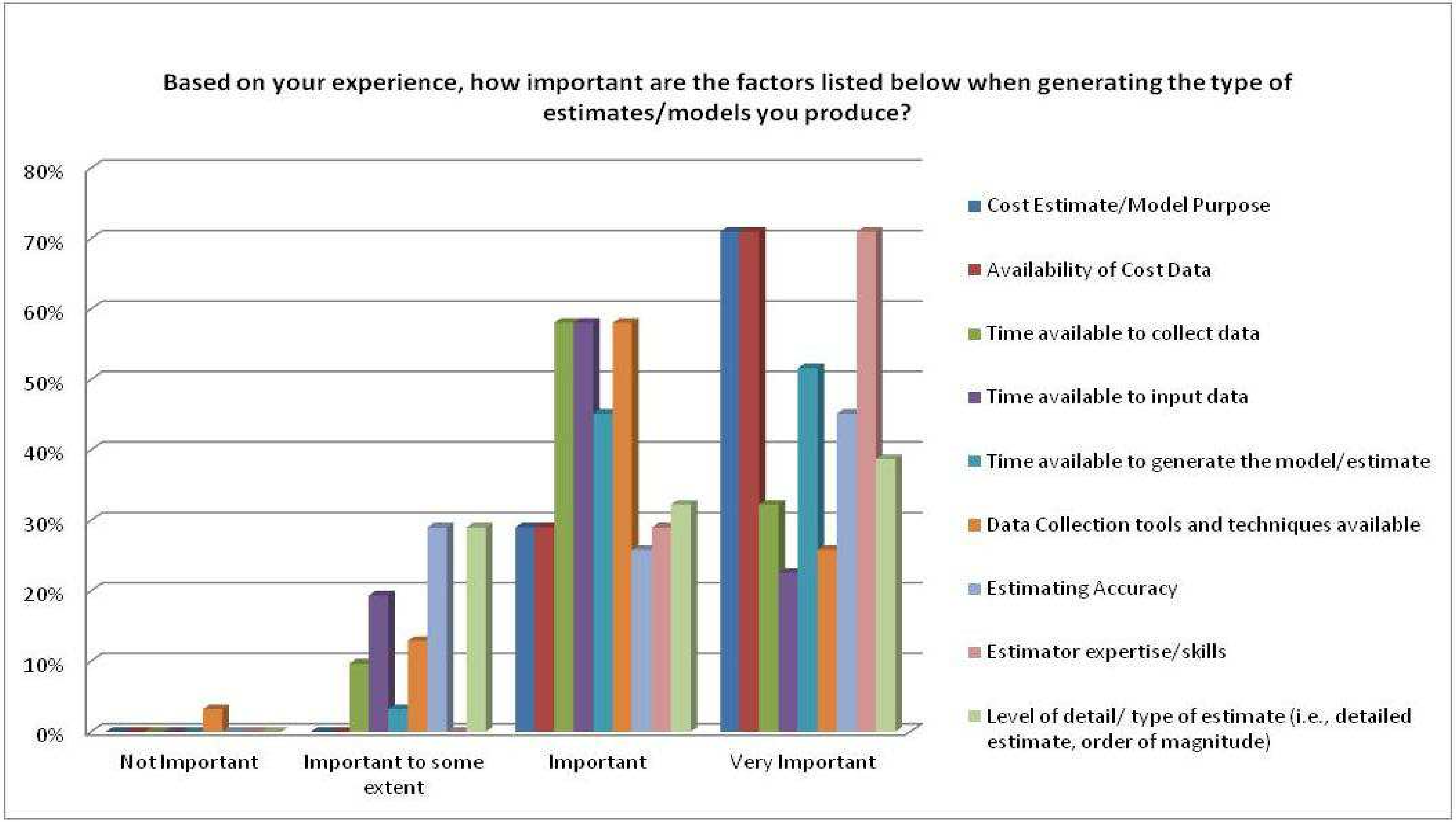


Figure 5.9 Factors affecting the Cost Model Development Process

One common issue mentioned in the literature and identified from the surveys is the long lead times of the tasks in the CMDP. It has been well documented that activities such as data identification and collection are time consuming and sometimes labour intensive. Figure 5.10 shows the answers given by the participants based on their experience on the average lead times of the different steps in the CMDP. Based on the responses given, the following inferences have been drawn:

- Deciding on the most representative product or process to be costed may take between a few hours up to a few weeks.
- The identification of product and process data to be collected predominantly takes weeks.
- In most cases, the cost model characteristics are defined in a matter of weeks.
- The identification of data sources and information to build the model can mainly take between a few weeks up to some months.
- In the main, the identification of data collection tools, techniques and/or methods takes weeks. However, it can also take either a few days or some months. This may depend on the type of data to be collected and its availability, on the skills and experience of the cost model developer collecting the data, on the level of detail of the model among other factors already discussed.
- The above factors (i.e., type and availability of data to be collected, skills level and experience of the cost model developer collecting the data, level of detail of the model) will also affect the actual process of collecting the cost data and information for the model. Collecting process and product data can take weeks, but predominantly takes months and in a few cases even years.
- Identifying cost drivers can be done mostly in a few weeks, while identifying and collecting the input data to build into the model requires between a few weeks and some months in most cases.
- Activities involving structuring and analysing data to define the cost model or estimate (data handling) and tasks concerning testing the validity and estimating accuracy of the cost model/estimate predominantly takes weeks, but could also take days or months.

- Finally, applying models within the business can be done between days or take up to some months.
- Some tasks may take even years to complete. These tasks include collecting process and product data, identifying data needed to build the cost model and collect data; structuring and analysing data to define the cost model/estimate; testing validity and estimating accuracy of the cost model/estimate; applying models within the business. The fact is that as long as the model is in use within the business, these tasks may be conducted in a recurring iterative way in order to update and maintain the model's validity.

The above statements are the result of the analysis of the information provided by the respondents of Questionnaire II. Although the response rate implies that this is not a representative sample of the total population, it can be said that the conclusions of the above analysis are not far from being the common case scenario for cost modelling exercises as suggested by studies found in the reviewed literature and by cost model practitioners interviewed during the survey Questionnaire I exercise.

High survey response rates are important to ensure that survey results are representative of the target population. Response rates are even more important when the purpose of the study is to measure effects or make generalisations to a larger population, as some statistical procedures and calculations are to be conducted for the analysis, which require a minimum sample size. Nonetheless, the response rate is less important if the purpose is to gain an insight.

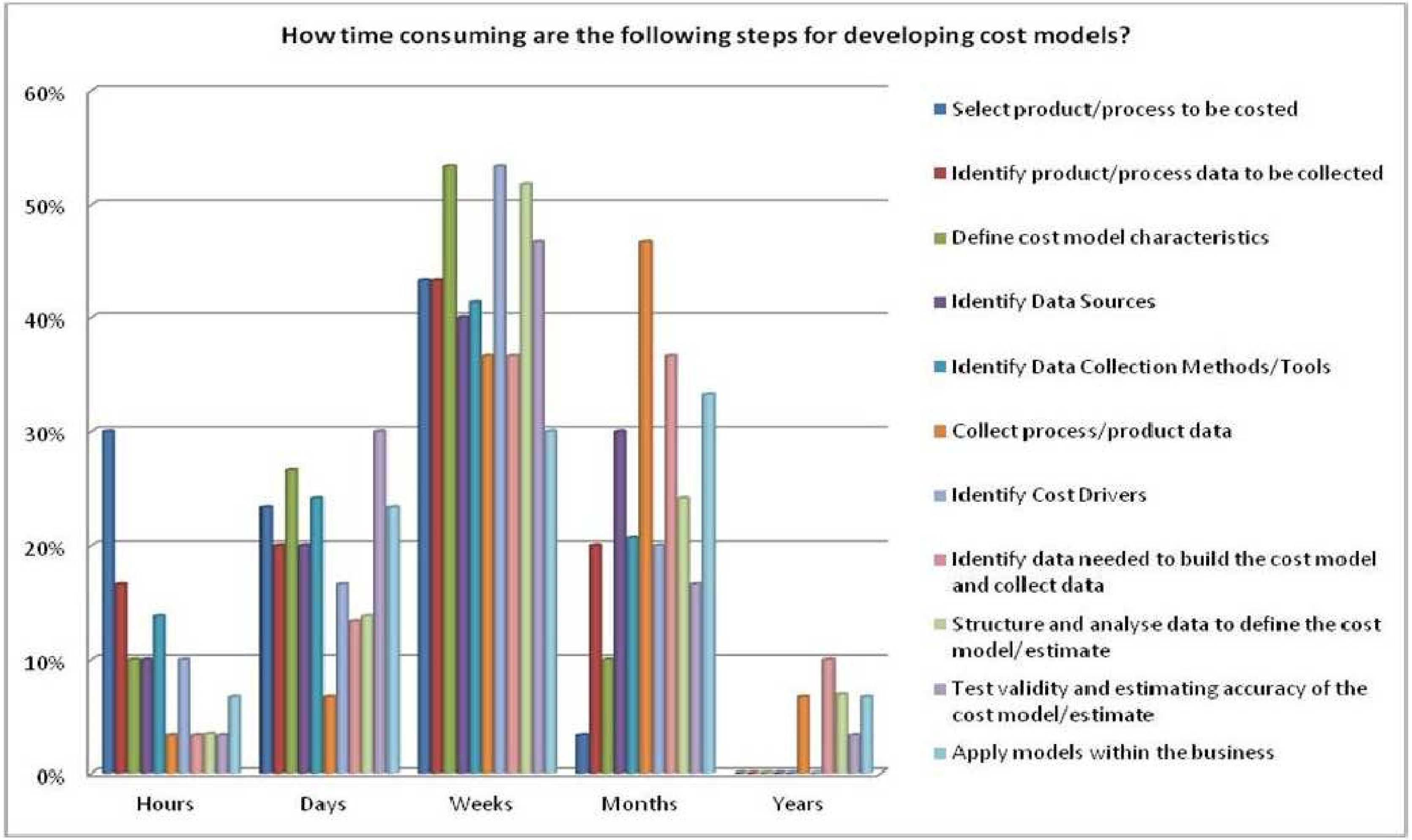


Figure 5.10 Lead times associated with the different tasks involved in the Development of Cost Models

With this in mind, respondents were asked about the features they would like to see that aids their cost modelling process (Question 21). The answers from those who completed the question are listed below:

- “Set procedures and formats for each style of model in order to ‘speed up’ the process”
- “Good documentation by model builders, change control; more automation and Uncertainty Analysis”
- “Structured Data Storage in the Organisation”
- “Visual Aids...a picture paints a thousand words”
- “Sensitivity study; model transparency; consistency (use of the same units for cost rates)”
- “Standard process for Benchmarking and the development process”
- “Common understanding; simplicity; consistency; no time consuming”
- “Risk analysis and coherent development procedure”
- “More structured cost modelling process for more visibility”
- “More visibility within the process”
- “Traceability of data and information” ”Standard cost modelling methodology and process improvement as the process is currently based on suppliers' information and processes (2nd hand data) rather than in house manufacturing”
- “Consistency in the modelling process and common central database to store CERs. Common software platform throughout functions to build cost models.”
- "More accurate, genuine and up to date data available. Standardised Modelling Process.”
- "More effective and efficient (less time consuming) data collection task More reliable data sources "
- "Commonality. Ability to track and show information and steps in the process System integration"
- "Suppliers' cooperation Definition of Model purpose"

- "More structured approach to develop cost models (process) Consistency and visibility when managing data and information (inputs and outputs)"
- "General Database of Process and product features and process activities. Training on the use of data collection methods and online resources (technical databases, patents search and electronic versions of papers) and tools such as Motion and Time Study."
- "More structured and standardised approach/process. More visibility and traceability along the process steps"
- “More structured and standardised process along the whole business”
- “Extract usable data from SAP automatically”
- “I've just received a new laptop .... my previous one had been far too slow !!.... seriously, for the products we buy it would be wonderful to be able to use a generic model, however our suppliers are either very big corporations (for whom our business is...”
- “Always need more cost data that can be traced back to original raw data. Technical/programmatic characteristics associated with cost data are also very important.”

The responses above suggest that there are some common needs including:

- A more structured and consistent model development process
- Mechanisms for data and information traceability
- Process Visibility
- Appropriate data sources (updated, right format, accurate) and databases and suitable data collection techniques and methods (including training)
- Cooperation from different stakeholders and sources of information in defining the Model Purpose.
- Visual (pictorial) aids, Commonality and System integration
- Automation and common software platform throughout the business to build cost models

The outcomes of the present research work potentially aim to deal with the first five issues described. As for the last two, future work could be focused on answering those needs by proposing solutions to address them. Virtual reality and discrete event simulation could be integrated to product and process feature databases throughout appropriate interfaces, programmes and software; and these to the data sources and data collection tools in order to not only identify cost drivers but to advice on potential data types, their data sources and then suggest data collection tools, techniques or methods to elicit the required information at the appropriate level of detail.

As discussed in previous chapters, cost models are built to serve a purpose. Cost models are useful tools for:

- Identifying opportunity windows for process/product improvement.
- By supporting product and process estimates.
- Maximising productivity and eliminating waste.
- They are useful tools to obtain process and cost information for decision making.
- Cost models are instruments for cost estimation in the early stages of the product development process, when 80% to 85% of the product's whole life cycle costs are committed.
- They are also a main element and a starting point of product life cycle cost management (Woodward, 1997).
- Decisions on product variations, the use of standard parts, distribution channels, make or buy and lot size often involve trade-offs between product cost structures and market required performance characteristics. Accurate cost models will inform such trade-off.
- In summary, they are tools to assist companies to gain and maintain competitive advantage.

It has been established the significant importance of the purpose of the model not only in the literature but also it has been identified by the respondents of both surveys. As described in Chapter 2, models can be built for a number of business objectives. As per Figure 5.11, among the respondents, cost models are most commonly used to support the decision making process for cost reduction; pricing and quotations; procurement and manufacturing decisions. The next group of business objectives down in line include those decisions concerning product development; product evaluation; product improvement and Target Costing. These business objectives may be mostly established at the higher levels of the management hierarchy within the business. This seems to be consistent with the results shown in Figure 5.12, which indicate that the models developed by the participants are predominantly used for business decisions and objectives located at strategic levels. Models developed for the second group of decisions and business objectives are principally related to production and manufacturing cost and cost control, cost planning and cost management. These are functions primarily located at tactical and operational levels.

At the other end of the spectrum, there are business objectives for which the development of a cost model is still conducted but seem to be more restricted, probably because of the very nature of the activities involved or because there is no economical justification for it to take place. In other words, the perceived benefits, cost savings or final value added do not justify the cost associated with the development of the cost model. These business objectives include Standard Data Generation, Capacity Planning and Production Scheduling. Future work in this area may involve looking at the reasons why cost models are developed for certain business objectives and purposes in order to build some kind of decision making criteria to assist cost model developers in deciding whether a model is worth developing.

A number of business objectives were identified by the respondents including: Design Optimisation; New Product Introduction; IRR (Internal Rate of Return) and NPV (Net Present Value); Budgeting, Analysis of alternatives, Source Selections, Support for Cost Negotiations, DoD Milestone decisions (Is system ready to transition to next acquisition phase?).

Risk analysis consideration was mentioned as an important cost model feature at the Exploration stage when the Questionnaire I survey was carried out. More than half of the participants in the Questionnaire II survey considered Risk as an important element in the CMDP. However, it is not clear yet at this stage whether Risk should be part of the factors to be taken into account when defining the cost model characteristics (in addition to the process features and model characteristics) and therefore pre-established by Management, the model user or any other of the stakeholder of the model. Or whether this should be a feature to be built within the model.

It was suggested by one of the Senior Cost Engineers at one of the Aerospace companies participating in the research that, either way the level of risk should be verified and/or validated as with the accuracy and precision of the models.

Further discussions with the same Senior Cost Engineers suggested that, precision and accuracy, and even sensitivity could be used as measures for Risk. For instance, after changes in design, for a model with high level of sensitivity any change in the input parameters may have an effect on the accuracy of the model, whose range may shift or widen. The model characteristics and purpose will help to establish whether that change in the accuracy is acceptable or not; hence the risk to be taken. This may be another area for future work.

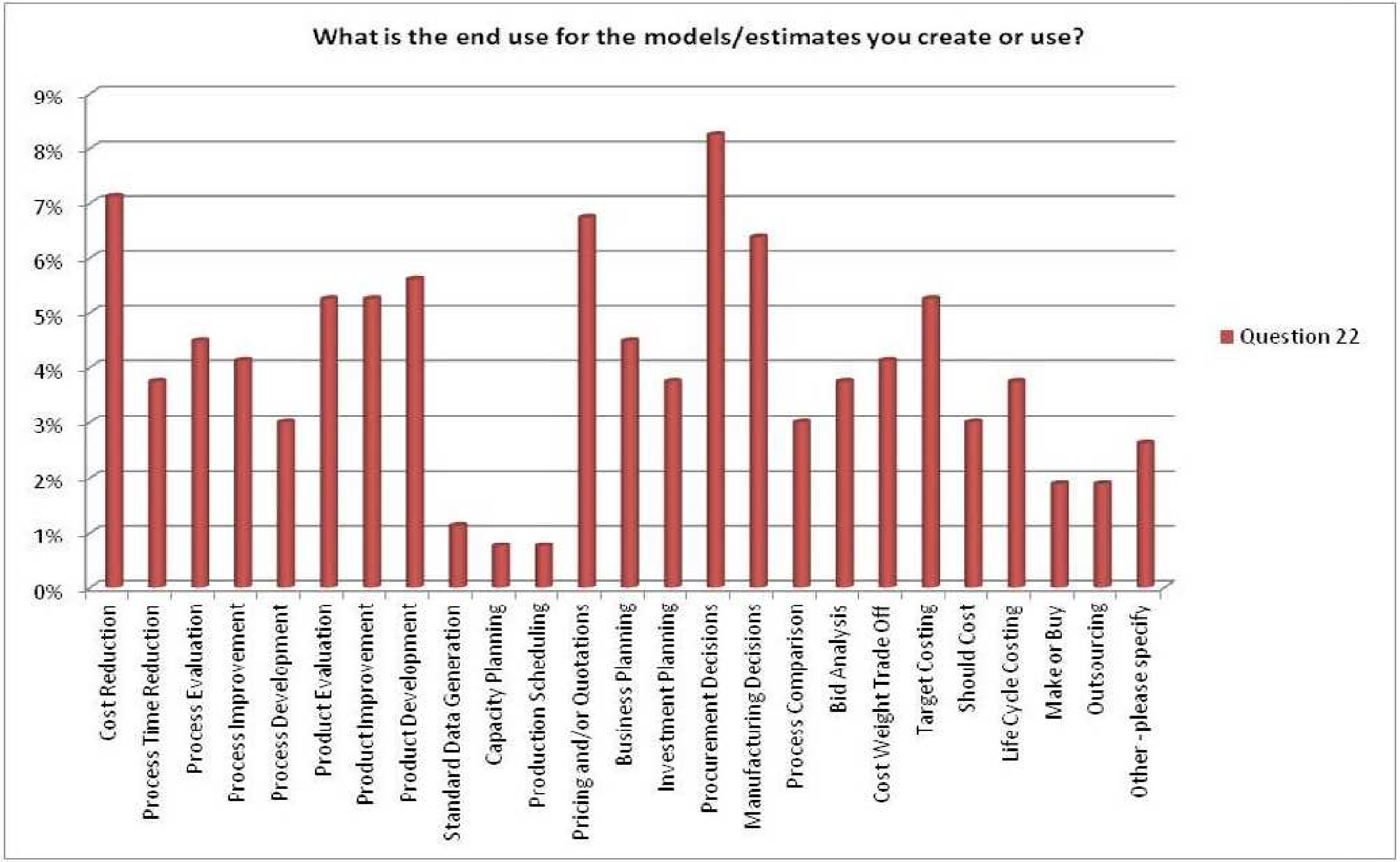


Figure 5.11 Business Objectives the outputs of the cost models and estimates are used for

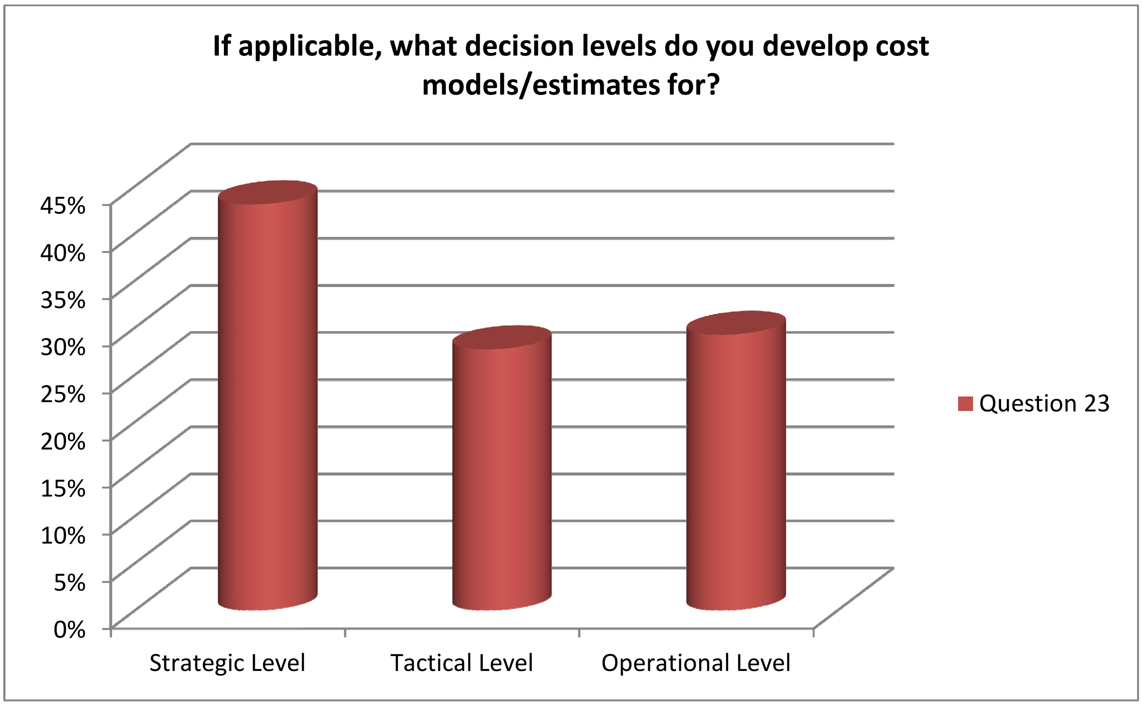


Figure 5.12 Decision making levels cost models are developed for

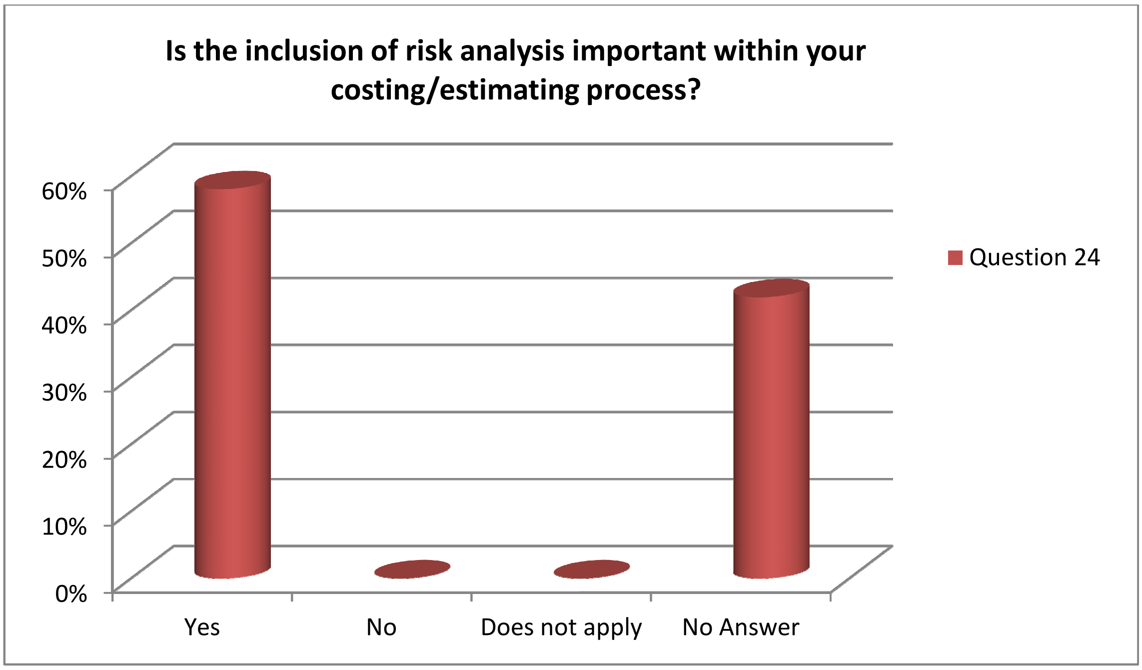


Figure 5.13 Risk analysis considerations in the cost model development process

Because of the low response rate (18%), in-depth statistical data analysis was not possible or feasible. Consequently, the conclusions drawn from the analysis of the data from this exercise on this sample cannot be taken as representative of the whole community of cost engineers and estimators. Nevertheless, the information provided by the respondents was used as part of the input for the focus group exercises described below and later on for the Evaluation and Validation stages of the research methodology. Responses also contributed to build up the Library of Data Sources and Data Collection techniques, tools and methods.

5.3.2 Focus Group Exercises: Input Data Types, DS and DC-TTMs

This section deals with the analysis and discussion of results from focus group exercises conducted during the Formulation stage of the research methodology. The participants were cost modelling and estimating engineers working at British Aerospace Airbus (Filton site in Bristol), Rolls-Royce (Derby and Filton sites, in Derbyshire and Bristol) and British Aerospace Systems, Military Aircraft & Aerostructures (Wartonsite in Preston, now Military Air Solutions - MAS) and at two of their suppliers Diamonite Aircraft Furnishing Ltd (Fishponds, Bristol) and Hyde Group Ltd (Dukinfield, Cheshire). Academics working in the area of cost modelling also took part.

The groups consisted of a minimum of 6 to a maximum of 12 people. The participation rate was very much limited to the participants' availability as the exercises used to take between 2 hours and 6 hours depending on the objective and steps involved in the sessions.

5.3.2.1 Identifying and selecting Input Data Types using the PC Matrix

This objective was achieved using the Paired Comparison (PC) method as described in Chapter 4. A pilot test of the procedure was initially conducted completing the PC-Matrices using a Base of a Drill Stand for a Bridgeport CNC Milling Machine Centre. A number of processes (Table 5.5) at the participant companies were also discussed and a copy of the paper version of the PC Matrix was completed. The outputs of the exercises were used to build a Library of Data Types, namely, Process and Product Features and Process Activities for each of the processes looked at. A sample is shown in Figures 5.14a, 5.14b and 5.14c for the DDF Process for the manufacture of Spars.

THERMOFORMING OF SPARS COMPONENTS USING DDF

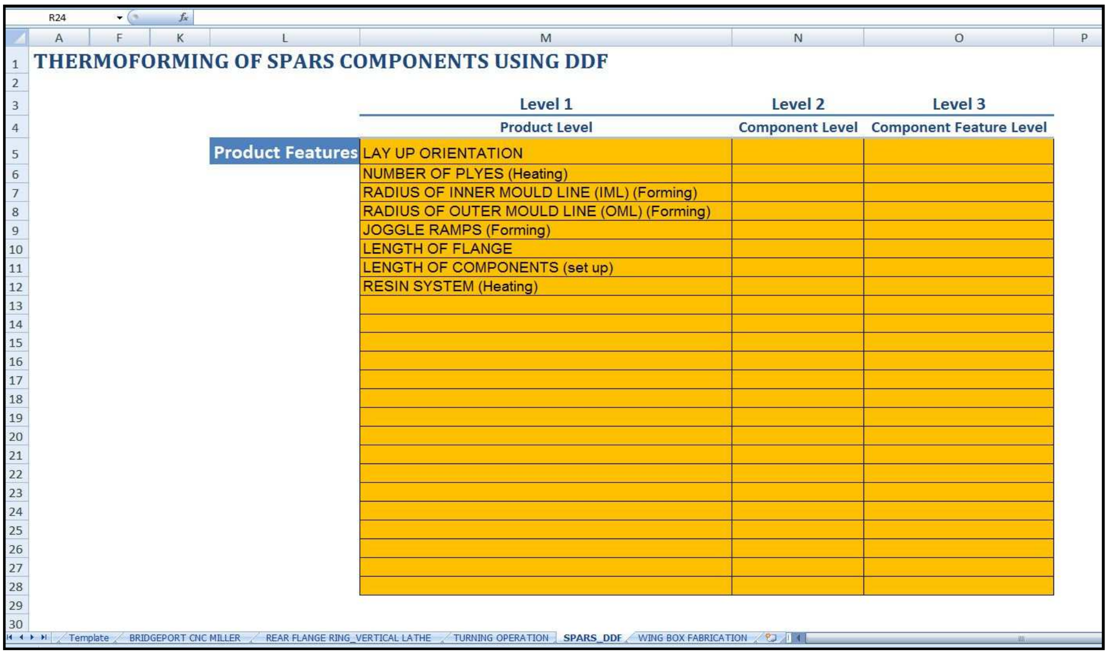
	Level 1 Process Level	Level 2 Process Operation Level	Level 3 Operational Activity Level
Process Activities	LOADING	RAISE HEATER	
		EXTENT TABLE	
		COLLECT/PREPARE ANCILLIARIES	
		LOAD TOOL TO TABLE	
	SETUP	POSITION MEMBRANE #1	
		POSITION PREFORM AND THERMOCOUPLES	
		POSITION MEMBRANE #2 AND SEAL (")	
		APPLY TENSION	
		RETRACT TABLE	
		LOWER HOOD	
	FORMING (CYCLE START)	HEAT APPLIED	
		DWELL	
		VACUUM APPLIED	
		DWELL	
		COOL	
		VACUUM RELEASE	
	UNLOADING	RAISE HOOD	
		EXTENT TABLE	
		REMOVE MEMBRANE #2	
		REMOVE COMPONENT	
		REMOVE MEMBRANE #1	
		REMOVE TOOL	
	POSITION MEMBRANE #2 & SEAL	POSITION RELEASE FILM	
		POSITION BREATHER	
		LOCATE TENSION PINS	
		POSITION VACUUM BAG	
		SEAL VACUUM BAG	
		LOCATE MEMBRANE ASSEMBLY TO FRAME	

Figure 5.14a Process Activities - Double Diaphragm Forming for the manufacture of Spars

THERMOFORMING OF SPARS COMPONENTS USING DDF

	Level 1 Machine Level	Level 2 Machine Assembly Level	Level 3 Sub-Assembly Level
Process Features	MALE FORMING TOOL		
	VACUUM FORMING MACHINE	HEATING CONTROLLER	
		VACUUM CONTROLLER	
		RECORDING SYSTEM	
		COOLING SYSTEM	
		VACUUM SYSTEM (**)	LIGHT BULBS (*)
			SILICON BAG (**)
			TENSION MEMBRANES (**)
			RELEASE FILM (**)
			BREATHER LAYER (**)
		HEATING SYSTEM (*)	
		MEMBRANE (**)	
		MECHANICAL MOVING TABLE/HOOD	

Figure 5.14b Process Features - Double Diaphragm Forming for the manufacture of Spars



THERMOFORMING OF SPARS COMPONENTS USING DDF

	Level 1	Level 2	Level 3
	Product Level	Component Level	Component Feature Level
Product Features	LAY UP ORIENTATION		
	NUMBER OF PLYES (Heating)		
	RADIUS OF INNER MOULD LINE (IML) (Forming)		
	RADIUS OF OUTER MOULD LINE (OML) (Forming)		
	JOGGLE RAMPS (Forming)		
	LENGTH OF FLANGE		
	LENGTH OF COMPONENTS (set up)		
	RESIN SYSTEM (Heating)		

Template / BRIDGEPORT CNC MILLER / REAR FLANGE RING_VERTICAL LATHE / TURNING OPERATION / SPARS_DDF / WING BOX FABRICATION

Figure 5.14c Product Features - Double Diaphragm Forming for the manufacture of Spars

There is a paper-based version of the PC Matrix as well as an electronic version developed in MS-Excel. The forms were completed using the paper-based version and then the information collated was fed into the Excel version of the PC Matrix.

The PC method is intended for use with multi-skilled groups who should move through the sequence of individual work sheets creating and inputting the required information. The Model developer will need to collect the appropriate data concerning the products and processes for which estimating models are being developed prior to the group work being undertaken. It is expected that the PC Matrix will be used to produce relationships between the product features, process activities, process features and the resources, which will in turn allow the creation of a cost model. This cost model to be developed shall be created from these relationships that are identified, most probably in the form of a CER.

Process Time was the Resource chosen by the participants to work on every exercise. A possible reason may have been the implications of confidentiality and the commercial sensitivity around the other resources or costs or that the participants did not have a clear understanding of the currency and conversion rates involved as, in some cases, they may be added to the cost model output just before calculating the required cost estimates. Process time may be the only relationship that has any real significance in this instance or was the only resource that was available.

A secondary aim of these activities was to test the effectiveness and suitability of using PC for collecting information on cost elements for the development of cost models. The following paragraphs summarised the analysis and views gathered from the exercises.

Company	Process	Resource Costed and Level	Dependant Cost Element	Predictor Cost Elements
DMU	Drill Stand Base for a Bridgeport CNC Miller	Direct Process Time/Level 3	Process Activity	Product and Process Feature
C	5-Axis CNC Machine	Process Time/Level 1	Process Activity	Product and Process Feature
A	Rear Flange Rings – Vertical Lathe	Process Time/Level 1	Product Feature	Product and Process Feature and Process Activity
D	Spars – Double Diaphragm Forming (DDF)	Process Time/Level 1	Product Feature	Process Feature and Activity
D	Wing Box Fabrication	Recurring Process Time/Level 1	Product Feature	Process Activity and Process Feature

Table 5.5 Processes and Products used for identifying Product and Process features and process activities using the PC method

The PC forms were completed using expertise and subjective opinion at a rather high level of detail to determine the features and activities that make the major contributions to cost. Cost drivers are the quantities that drive the cost of the process or product the most, in other words, the quantities that contribute to the cost the most in an known or unknown relationship, that maybe exponential, linear or quadratic (CERs).

In terms of the features and activities identified, some cost elements were established as the potential cost drivers of the cost resource under consideration (namely, process time). This was achieved by determining the effect of the product and process features and activities on the resource to be estimated and the relationship between each element identified against the others within its own level; this is between elements at the same level (product and process features at level 1 only, for instance). In this sense, the PC method may be restrictive and the effect and relationship between elements at different levels of detail is still to be established by means of other methods such as Relational Matrix, Pareto Analysis, for example.

At the end of the exercises the participants provided their opinions and suggestions on the format, content and structure. Suggestions on including Product Tree Structures for Product and Process resources to be costed and for levels of Product/Process

Features and Process Activities were made as some of the participants could not differentiate between the different levels of the cost elements despite being briefed on the levels and types of cost elements and on the process and product being investigated before conducting the exercise.

Information required for the sessions was made available, including data on product features such as photos of components of a certain product range, engineering drawings or finished components. For process features, photographs and diagrams (process flow diagrams) showing typical sequence of tasks of the manufacturing processes were provided. Some of the participants have some knowledge of the process. The familiarisation of the process and the range of products produced occurred before the focus group exercises took place, or just before the exercise to ensure maximum familiarity. Yet it seems that some participants did not have a full understanding of the process.

Visual aids and information already available, including product drawings, checklist of operation activities, operation times and machine specification, were found to be important as the experts could readily identify the required data when the information was there for them to identify from.

It was agreed that some levels were not applicable to all processes. This depends on the type of resource to be costed. For instance, Process Features may be relevant for resources such as Cost of Investment; however, it might not be relevant for resources such as Process Time. It was evident, though, that the participants experienced difficulties to conceptualise the levels that were set.

Identification of the Process Features was found to be challenging as the operation that produces certain product feature may also be on a set machining path that incorporates several other features.

Assumptions and a number of considerations had to be made along the way in the process, so that the amount of information at the lower levels could be reduced. Hence, for the manufacturing of Rear Flange Rings, for example, it had to be assumed that the machine or process was capable of handling the size of the component. This in turn assumed that the machine had enough power to machine the component; the chuck was large enough to handle the tool; the bed size was large enough to accommodate the material and the speed (rpm) was sufficient to perform the machining task.

On the other hand, some products are so simple that it makes it difficult to identify the most relevant Process Features. For example, the identification of the product features was found to be at a far too high level for the Rear Flange Rings manufacturing process, with only one entry for the upper levels (Product and Component level) as shown in Figure 5.15. This may be down to the product being a ring which is manufactured from a casting and this one piece is machined down to size.

The inherent simplicity of the product is such that it has no sub-assemblies or inserts which results in that the only high level information available is the fact that it is a ring as far as product features are concerned. Features for casting or cost drivers associated to the product’s material, for example, weight and thickness, which should have been included in this category, were not mentioned by the participants. In the same way, at level 3 (component feature level) although a substantial amount of data was identified, important attributes such as tolerances for external diameter, for example, were not identified by the respondents.


Rear Flange Rings_Vertical Lathe

	Level 1	Level 2	Level 3
	Product Level	Component Level	Component Feature Level
Product Features	Rear Flange Ring	Rear Flange Ring	Top Surface
			External Diameter (1)
			Shoulder
			External Diameter (2)
			Flange (1)
			External Groove
			External Diameter (3)
			Radius
			External Diameter (4)

Figure 5.15 Product Features for Rear Flange Rings

Additionally, it seems that in some cases, cost elements such as Process Features and Activities might have the same entries (duplicate information) at different levels (Figure 5.16). For the Turning Operation, for example, process activities identified at Level 1

(Process Level) are also entries for Level 2 (Process Operation Level) and Level 3 (Operational Activity Level). This may be the result of the participants' lack of understanding on the level definitions; their own individual interpretation, lack of consensus or *'all of the above'*.

Turning Operation

	Level 1	Level 2	Level 3
	Process Level	Process Operation Level	Operational Activity Level
Process Activities	Turning	Tool Change	Clamping
	Boring	Threading	Part Off
	Drilling	Knurling	Radii
	Reaming	Reaming	
	Threading		
	Radii		
	Facing		
	Knurling		
	Part Off		
	Clamping		
	Safety		
	Swarf Remove		
	Deburr		
	Load Component		
	Unload Component		
	Tool Positioning		
	Loading Tool Mechanism		
	Tool Changing		
	CNC Programming		
	Inspection		
	Maintenance		
	Manual Manipulation		
	Speed Changes		
	Coordinate Measuring Machine		

BRIDGEPORT CNC MILLER / REAR FLANGE RING_VERTICAL LATHE / TURNING OPERATION / SPARS_DDF / WING BOX FABRICATION

Figure 5.16 Process Activities for Turning Operation

For those processes over which participants or their organisations have control, the PC method at all levels (including Process features) will apply (for example, assembly). However, for those processes at their suppliers' facilities for which they have no control over or access to, the identification and collection of Process features may not be feasible or viable.

As an improvement measure for future use, it may be necessary to include a Criteria for Comparison for the items identified in the Paired Comparison form; for instance *'the longest process time', 'activity which adds most to the cost', 'charge rate'*, among others, according to the case. Another improvement could be including examples of Family Tree diagrams for different processes and a Library of terms and definitions within the form. It should also help to list the assumptions and/or considerations about the ideal or expected (minimum) conditions for the process and product.

This highlights the need to define the purpose and scope of the model along with the process and product characteristics before getting into the task of identifying the cost elements and level of information to be considered as input for building the model

With regards to the levels of the data types, they may still serve the purpose of guiding the selection of the data sources and data collection techniques as discussed in the following sections.

5.3.2.2 Linking DS and Input Data Types

A focus group exercise was set to identify the data sources available for different process elements and their levels. An adapted version of relational matrix was prepared, tested and used for this exercise. Using their own opinion and experience, group members determine the most suitable data sources for the most common resources being costed or estimated at the participant companies. At each of the different element levels (Table 3.3, Chapter 3), up to 3 potential data sources were chosen from the list provided (Table 4.6, Chapter 4).

Within each of the levels of product features, process features and process activities the data sources were established for the design development state of the process or product (namely, concept, preliminary design, prototype and commercial) and the resource to be costed. An example of the expected resulting input is shown below in Table 5.6.

Process Elements and Levels		Resources to be costed				
Product Feature		Material	Direct Labour	Indirect Labour	Process Time	Manning Levels
Level1	Product level					
	Concept	1.3, 1.4, 3.1	1.3, 2.2, 1.4	1.3, 1.4	1.3, 1.4, 5.1	1.3, 1.4, 10
	Preliminary design	1.3, 3.4, 3.6	1.3, 2.2, 1.4	3.1, 1.4, 5.1	1.3, 5.1, 3.2	1.3, 3.1, 4.3
	Prototype	1.3, 1.4, 3.4	1.3, 2.1, 2.2	1.3, 3.1, 2.2	1.1, 1.2, 1.4	1.3, 4.3, 5.1
	Commercial	1.3, 3.1, 3.4	2.1, 2.2, 6.3	1.1, 3.1 ,1.4	1.1, 1.2, 2.1	1.2, 1.3 ,1.4

Table 5.6 Section of the Data Sources (DS) vs. Data Types (Dtypes) Matrix

The data sources were evaluated by various factors and when collated the most suitable sources became apparent. These inputs were used to establish some kind of criteria for the selection of data sources and data collection methods according to the characteristics of the specified product or process and those of the required cost model.

The participants were provided with a paper-based copy of the full DC-Dtype Matrix, hand-outs explaining the different definitions of the process cost elements and their levels, Design Levels (adapted from Wierda's classification system for cost estimates) and a list consisting of the data sources codes and names as identified from the literature review and Questionnaires I and II, respectively. A brief presentation on the procedure to complete the Matrix, expected outcomes and definitions was given and questions from participants answered. Then they went away to complete the Matrix.

Following the completion of the DC-Dtype Matrix by the group members, the information gathered was uploaded for analysis onto a MS-Excel workbook. The data was analysed by using Histograms to show the relative frequency the different categories of Data Source that could be used to identify predictor variables (product and process features and process activities) for the different cost resources at different levels of detail and at different stages of the product lifecycle according to the focus group participants.

The data is presented for Direct and Indirect Material, Direct and Indirect Labour, Process and Elapsed Time Manning Levels and Tooling in Appendix C4. It consists of the overall results of the perceived capacity of each data source category to provide information (process features and activities, and product features) for each resource at different levels of detail and lifecycles stages. From the analysis of the data the following inferences were made:

- The stage of product development seems to have a stronger influence on the decision process for selecting data sources for a given resource than the level of detail of the cost element involved. In other words, the data source applied at Level 1 (Higher level) is also of use if information is still required at the lower levels of detail.
- Process Sources were identified as the starting point when looking for cost data and information for any resource, independently of the level of detail or product development stage. The process data sources generally referred to include similar processes and process experts at the early product development stages (concept and detail design) with

the addition of visual and control systems and actual processes later in the product lifecycle (prototype and commercial stages)

- One probable explanation is that either the participants' knowledge or awareness on the range of resources available to them is limited or those are the only data sources made available to them at their organisations.
- There are some data types for which only a limited number of data sources are suitable. For instance, when considering manning levels, sources such as shoopfloor documentation, operator's black book, and quality and maintenance manuals are the most appropriate means of information. Other sources may also be of use with some raw data handling and analysis to make the sources 'fit to purpose'. Even a 'bottom up' approach may be necessary in some instances. This will depend on the abilities and skills of the individual conducting the data identification and collection tasks.
- Not all Data Sources can be applied to all situations and their use will depend on the type of task involved and the additional data-gathering method used. They will also depend on the amount of data available.
- The identification of data sources for indirect costs such as indirect material and indirect labour present some degree of difficulty due to the inherent factors associated with the allocation of such costs.
- The selection of data sources was considerably influenced by the professional background and experience of the participants in cost engineering and modelling, but also by their data collection and identification skills particularly for those data sources which are less commonly known in industrial context (in the case of cost engineers) or for those data sources not available in the academic environment (in the case of the academic staff).

5.3.2.3 Linking DS and DC-TTMs

Building a cost model requires the use of appropriate data collection methods for each particular data source, having already identified what data is required for the model. The outputs from each stage of the development process are used as input for the next one.

It has been established from the literature review and the survey questionnaires that the data collection in the CMP is a time consuming process affected by the following factors:

- Availability of data sources
- Data types and level of detail
- Amount of data to be gathered
- Frequency of data collection
- Inconsistency in the data collection process.

Consequently, choosing the most appropriate data sources and data collection tools, techniques and methods represents an opportunity for significantly improving the CMDP by reducing the amount of data required to obtain a specific level of accuracy; reducing the time and resources required to collate the information and input it into the model as well as representing opportunities for increasing accuracy without compromising model complexity.

A DS-DC TTMs Relational Matrix was created and completed using the knowledge and experience of cost engineers and estimating practitioners from 5 organisations in the aerospace domain to identify the links between sources of cost data and potential data collection tools, techniques and methods identified from the literature review and survey questionnaires.

This section discusses the result obtained from the analysis of the DS-DC Relational Matrix. This phase of the work involved grouping the previously identified data sources and data collection techniques into categories according to their nature, main features and their application within the CMP. The following step consisted of establishing the links between the data sources and data collection methods for the generation of cost models. It was also the intention of the exercise to explore what new methods could be introduced within the CMP tasks of data collection.

After a pilot exercise, the matrix was completed, using the expertise from two focus groups whose participants were, respectively, academic and industrial experts in cost engineering and modelling. For the analysis of the data, techniques such as 'normalisation', 'scaling' and 'shifting' were used, in order to eliminate possible false trends and to help to visualise the effects of the different variables (Figure 5.17).

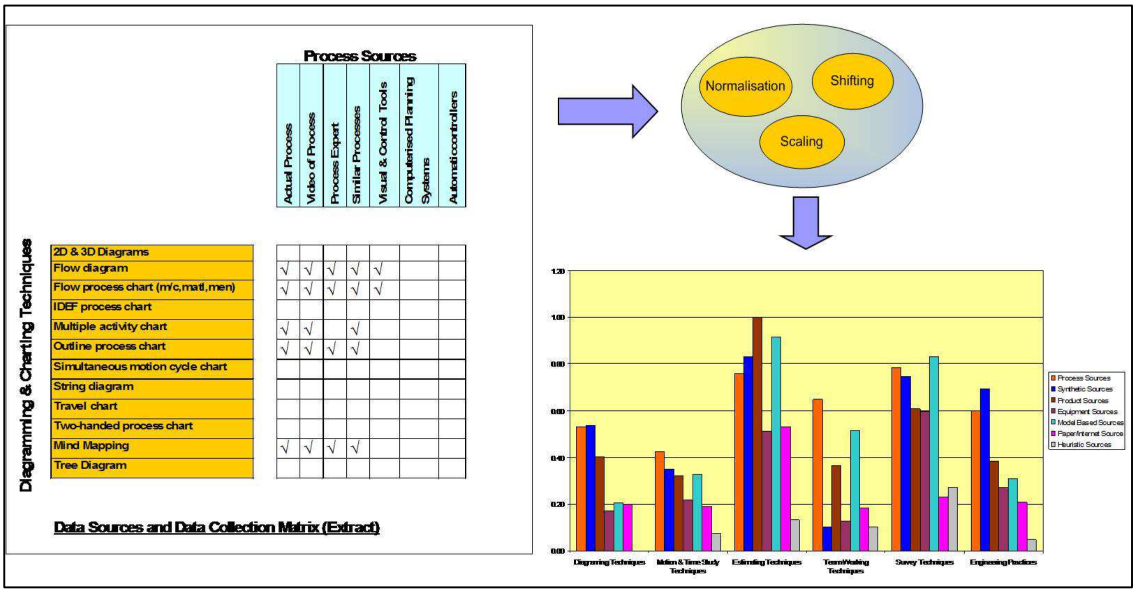


Figure 5.17 Results and Analysis - Data Sources and Data Collection TTMs.

The analysis of the results produced the potential data collection methods which can be used with each particular data source. The data was analysed based around the different categories of data sources (DS) and the categories of Data Collection tools, techniques and methods (DC-TTMs) which are either being employed or have the potential of being of use for the eliciting of data and cost information from each particular data source category. As discussed in Chapter 4, Pareto analysis was used for this purpose.

Based upon the outcomes from the focus group exercise, the information gathered from the analysis and the previous analysis on data sources and data types served as the basis for improving and updating the DS-DC TTMs library which will be incorporated as part of the proposed Cost Model Development Methodology.

A Taxonomy for Data Sources and Data Collection tools, methods and techniques was created. Seven categories of Data Sources, from which essential data for developing cost models could be collected, were defined to group a total of 33 Data Sources identified along the different stages of the investigation including those collected from the surveys, literature review, and interviews. A total of 35 individual methods, tools and techniques for data identification and collection were also identified and sorted into six data collection categories according to a set of generic features and individual characteristics including, for instance, what data sources and data types can be collected from their application, among others. A comprehensive list of data types was also produced. This provided essential information for selecting between alternative tools and techniques. This library of data sources, data types and data collection methods, tools and techniques constitutes an important source document and provides guidance and a starting point for the data collection tasks for the development of a cost model.

The main findings from this exercise and the rest of the work undertaken are discussed in the following paragraphs. Figure 5.18 and Figure 5.19 present overall results for the main categories of Data Sources and Data Collection Methods, respectively.

Data Sources – Overall Results by Categories

As shown in Figure 5.18, there were identified particular preferences to use certain categories of data sources and collection methods. It was also revealed that, within the same category, there were differences in terms of the preference for certain sources of data.

In terms of data sources, Process and Product Sources are the two most common providers of information; followed by Synthetic and Model based sources. They all ranked high for every category of data collection tools.

As expected, the primary and most important data sources identified within the Process Source category were manufacturing process experts.

Interestingly, Heuristic Sources obtained the lowest scores. This may have been caused by the participants not knowing for certain about the sources or not finding the possible applicability or relationship between the source and the data collection techniques, tools and methods.

It has to be mentioned that the popularity that a certain source had is influenced by the applicability of the data collection techniques for extracting the data from that particular source rather than the use of the source itself. In other words, it is driven by the applicability of the data collection techniques.

Data Collection TTMs – Overall Results by Categories

By looking at the data from the perspective of investigating the applicability of the different categories of Data Collection TTMs for extracting information from the various

DS categories, some inferences can be drawn. Figure 5.19 shows the results extracted from the analysis of the data.

In terms of DC categories, those with the higher scores (preference from the focus group participants) were Estimating and Survey Research Techniques; followed by ERMP, Diagramming and Charting Techniques, and WDME techniques. This predilection for the use of Estimating techniques, Survey techniques and Engineering practices, as data collection methods was indicated along the whole range of data source categories.

As before, the selection of the data collection techniques was driven by their applicability and appropriateness for extracting data from the given data sources.

It has to be noticed that some data collection methods, which have not been used for some time or used to a limited extent in the past and present times despite their benefits, are attracting some interest nowadays.

This is the case, for example, of Motion and Time Study Methods such as Activity and Work Sampling, Video tape recording and Film analysis sheet and Stopwatch Time Study from the WDME category. In the past, the use of these techniques was a source of preoccupation for trade unions (Currie, 1977; Nadler, 1963). However, since the introduction of the Lean philosophy in the Western industry, the perception of these tools has started to change from being seeing as intrusive and threatening control methods imposed by top management to techniques and procedures for improving working conditions and environment, increasing employees' motivation, and assist management in reducing unnecessary costs while helping employees to 'understand the nature and true cost of work' (Meyers and Stewart, 2002).

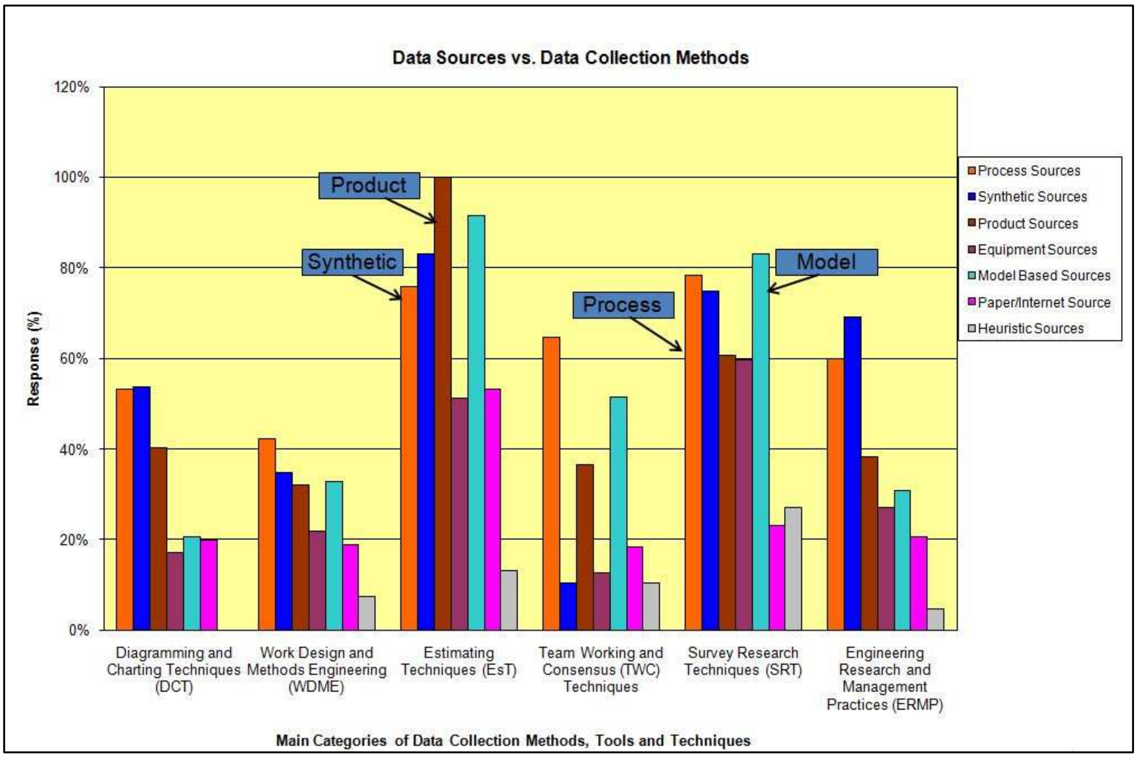


Figure 5.18 Overall Results for Data Source Categories

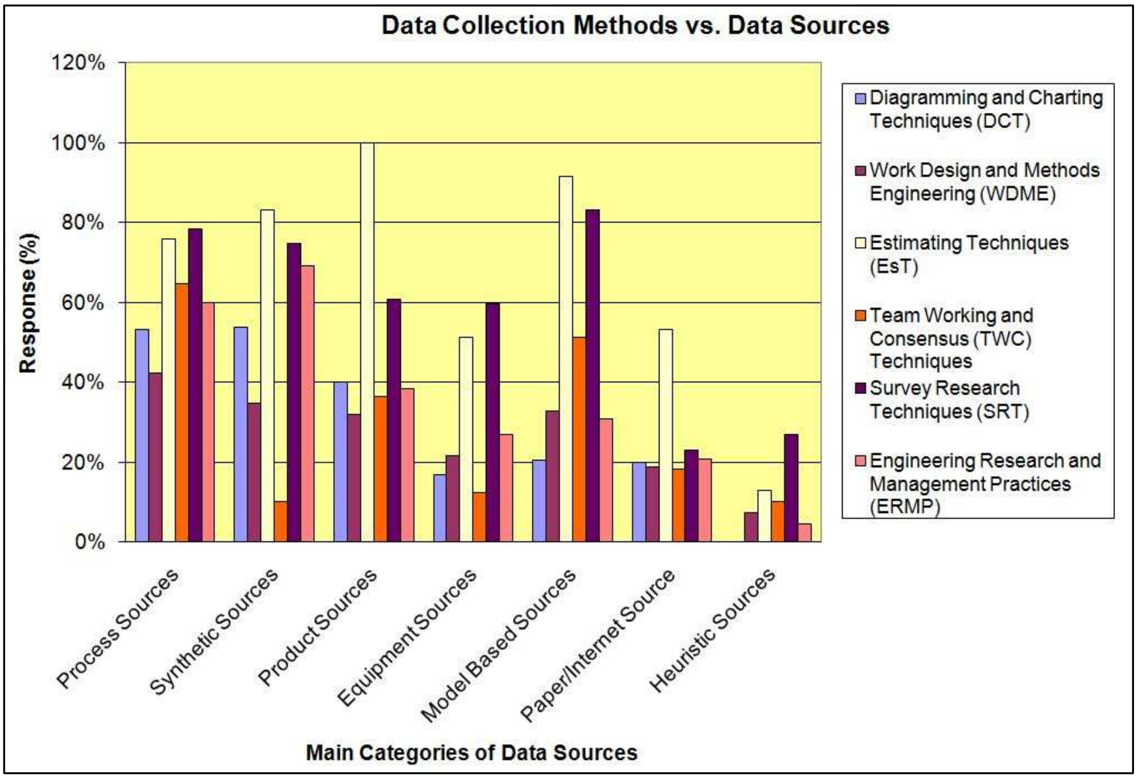


Figure 5.19 Overall Results for Data Collection Categories

In Table 5.7, the green-coloured cells indicate the Data Collection Categories selected for each Data Source Category after the Pareto Analysis took place. The ticks indicate the range of the percentage of response for each category according to the legend accompanying the Table.

DCT techniques are popular among different categories of data sources, particularly Process and Synthetic sources. WDME methods are preferred among Product Sources, but also used for collating information from Process, Synthetic, Equipment and Model sources. Estimating techniques find applications along all the categories, especially Process, Product, Synthetic and Model Based sources. Team working and Consensus techniques can also be of use for data collection along the whole range of Data Source categories, but it is most popular among Product, Process and Model based sources. Survey techniques seem to be applicable for eliciting information from a number of sources, mainly from Process, Synthetic and Model based sources; however, they are also common practice among Product and Equipment Sources. Finally, ERMP methods, find their main application for Product and Synthetic sources.

So far, it has been established that information regarding the level of detail of input data, model accuracy, data types, cost drivers and relationships between cost elements influence the selection of potential data sources and the decision-making process for selecting the most effective data collection tools. Factors which also have their effect on the data collection tasks are those associated with the cost model purpose and characteristics, and the actual product or process under consideration.

The knowledge and skills of the respondents in relation to the data sources and data collection tools, techniques and methods can also be either a major plus or a major constraint for the selection of the sources and data collection tools. These factors have to be taken into account when analysing the results from the focus group exercise on DS and DC TTMs potential links. Discussion of the results from the Pareto Analysis is provided in the following sections.

DATA COLLECTION TOOLS	DATA SOURCES						
	Process Sources	Synthetic Sources	Product Sources	Equipment Sources	Model Based Sources	Paper/Internet Sources	Heuristic Sources
Diagramming and Charting Techniques (DCT)	✓✓✓	✓✓✓	✓✓	✓✓	✓	✓	
Work Design and Methods Engineering (WDME)	✓✓	✓✓	✓✓✓	✓✓	✓✓	✓	
Estimating Techniques (EsT)	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓	✓✓✓✓	✓✓✓	✓
Team Working and Consensus (TWC) Techniques	✓✓✓	✓	✓✓	✓	✓✓✓	✓	✓
Survey Research Techniques (SRT)	✓✓✓✓	✓✓✓✓	✓✓✓	✓✓✓	✓✓✓✓	✓	✓✓
Engineering Research and Management Practices (ERMP)	✓✓✓	✓✓✓	✓✓	✓✓	✓✓	✓	

10% ≤ ✓ < 25%
25% ≤ ✓✓ < 50%
50% ≤ ✓✓✓ < 75%
75% ≤ ✓✓✓✓ < 100%

Table 5.7 Data Collection Categories vs. Data Sources – Results from the Analysis of the DS-DC TTMs Matrix's entries and Pareto.

Process Sources

Process Data Sources include Actual Process, Video of Process, Process Expert, Similar Processes, Visual and control tools, Computerised Planning Systems (ERP, MRPI, MRPII, and MPS) and Process Controllers (controllers of temperature, dimensions, among others). For this category, the responses indicated (Figure 5.20) that a variety of data collections TTMs could be used. There is no strong preference for a particular DC TTMs category. However, the data collection categories with higher scores were Survey Research and Estimating Techniques. At the other end, with lower scores, were DCT and WDME.

It would have been expected that, because of the nature of the Process data sources, DCT would have been a preferred choice for producing process flow diagrams for a process outline, Bill of Materials (BoM) for an assembled component, Work Breakdown Structures (WBS) for the process activities, just to mention some examples.

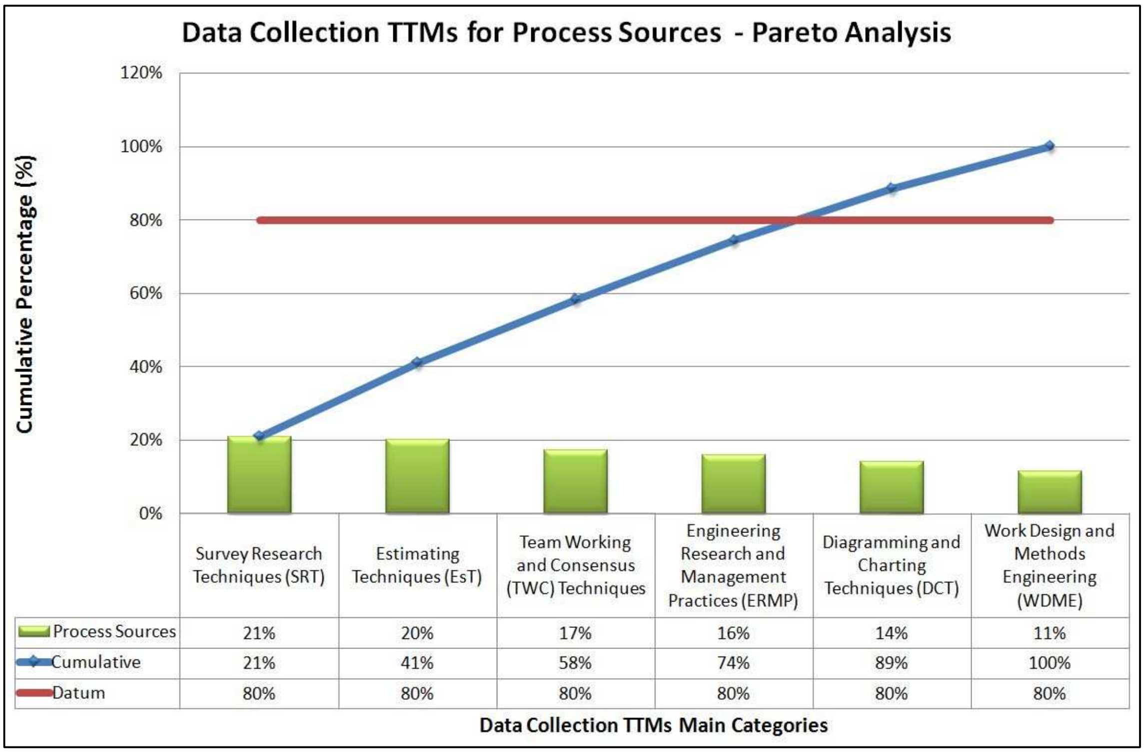


Figure 5.20 Data Collection TTMs for Process Sources – Main Categories

Synthetic Sources

These sources include Standard Data and PMTS systems. As shown in Figure 5.21, the main DC Categories for this data sources consist of Estimating, Survey Research and ERMP. Within the categories, the individual DC TTMs with higher preference among respondents were Analytical estimating; Interviews and Questionnaires; Critical Path Methods and Operational Experimentation.

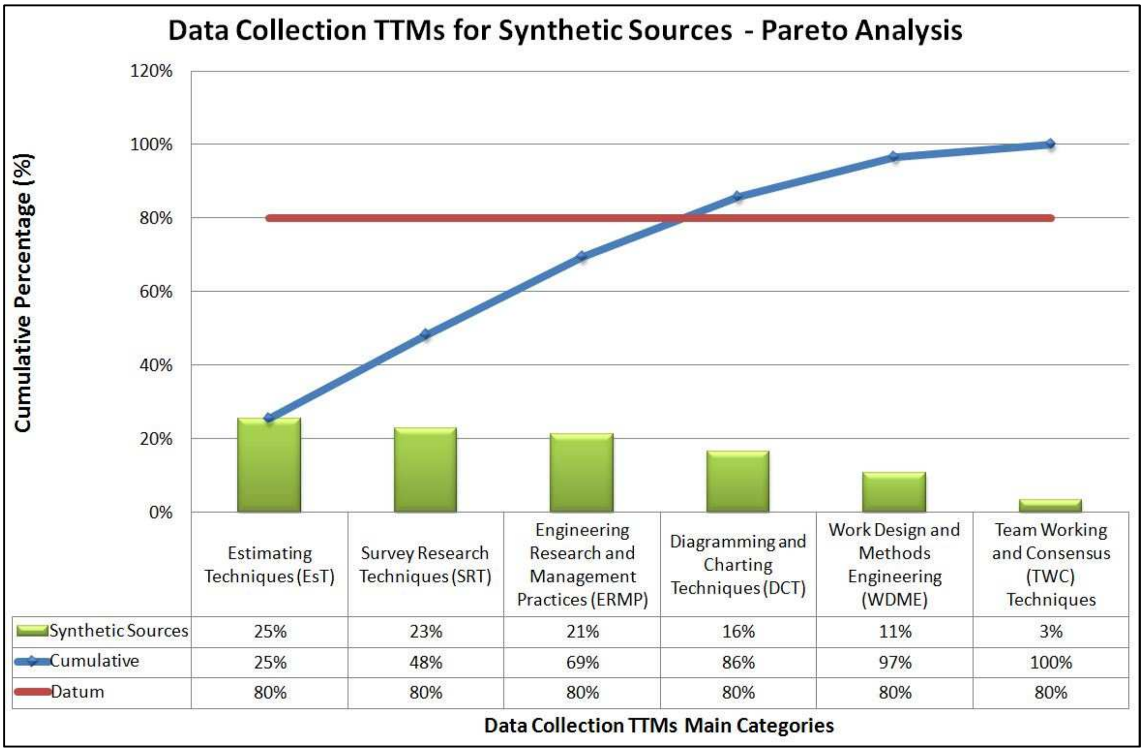


Figure 5.21 Data Collection TTMs for Synthetic Sources – Main Categories

Product Sources

This category consists of Costed Components, CNC Programmes, CAD Files, Product Specification, Bill of Materials and Engineering Drawings. The analysis showed (Figure 5.22) that the majority of the data collection tools, techniques and methods fall within the Estimating and Survey Research categories. The preferences were widespread among the Analytical estimating, Category estimating, Comparative estimating and Judgemental analysis technique for manual analysis of records, files, documents and computer analysis of records. Estimating techniques seem to be common practice within the cost analysis and estimation functions in the Aerospace Industry domain.

Interviews to process and product experts were also ranked high among the participants.

ERMP and DCT techniques are also of application, particularly Operational experiments, Critical Path Method, Flow process charting for machine material, and operator flow, as well as IDEF process charting.

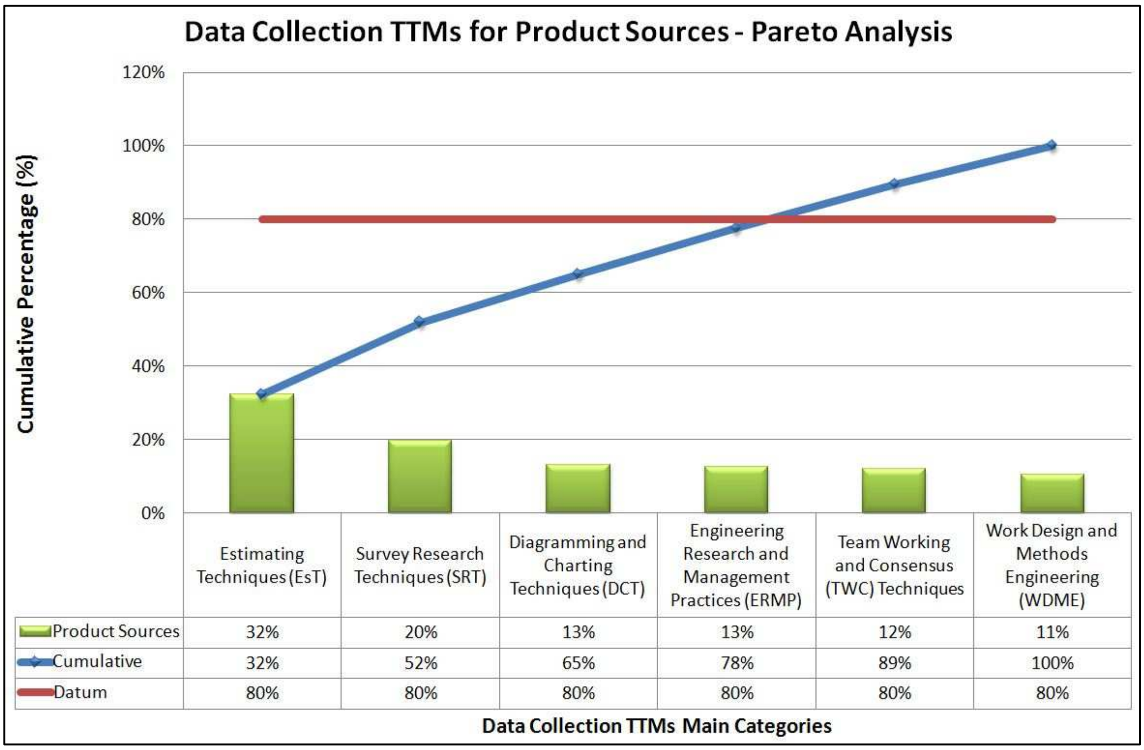


Figure 5.22 Data Collection TTMs for Product Sources – Main Categories

Equipment Sources

This data source category is made of documentation such as Equipment Specification, Maintenance Manuals, Operating Manuals, Training Manuals and Equipment performance records. The participants identified Survey Research Techniques (Figure 5.23); namely, Questionnaires and interviews with experts, as the main category of data collection TTMs to be of application for the collection of data from the above sources. As per the analysis, Estimating Techniques is the next category that follows. Considering the nature and characteristics of the data sources, it makes sense that the Judgemental analysis technique for the manual analysis of records, files, documents and computer analysis of records was revealed by the responses as the most suitable technique of this category.

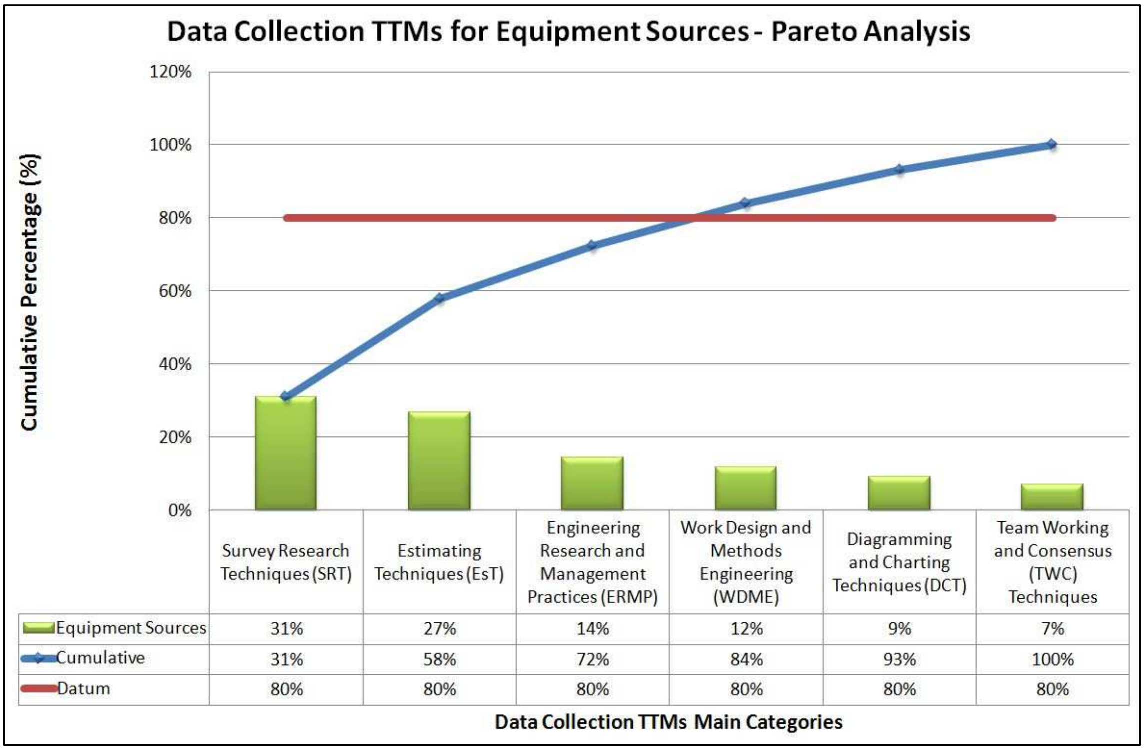


Figure 5.23 Data Collection TTMs for Equipment Sources – Main Categories

Model Based Sources

Process Models (such as software based or paper-based models), Empirical Laws and Physical Models are all included in this category of data sources. The respondents indicated that information from those sources could be collated using mainly Estimating and Survey Research Techniques, followed by Team Working and Consensus Techniques (TWCT) (Figure 5.24). It has to be pointed out that this last category was not considered by the participants as practical as the other two. The participants were somehow resistant to consider teamwork and consensus techniques as useful and viable tools for data gathering as the more traditional ones such as Survey and Estimating Techniques.

Analytical estimating, Interviews and Brainstorming were the individual techniques with the highest scores from each particular Data Collection category mentioned above.

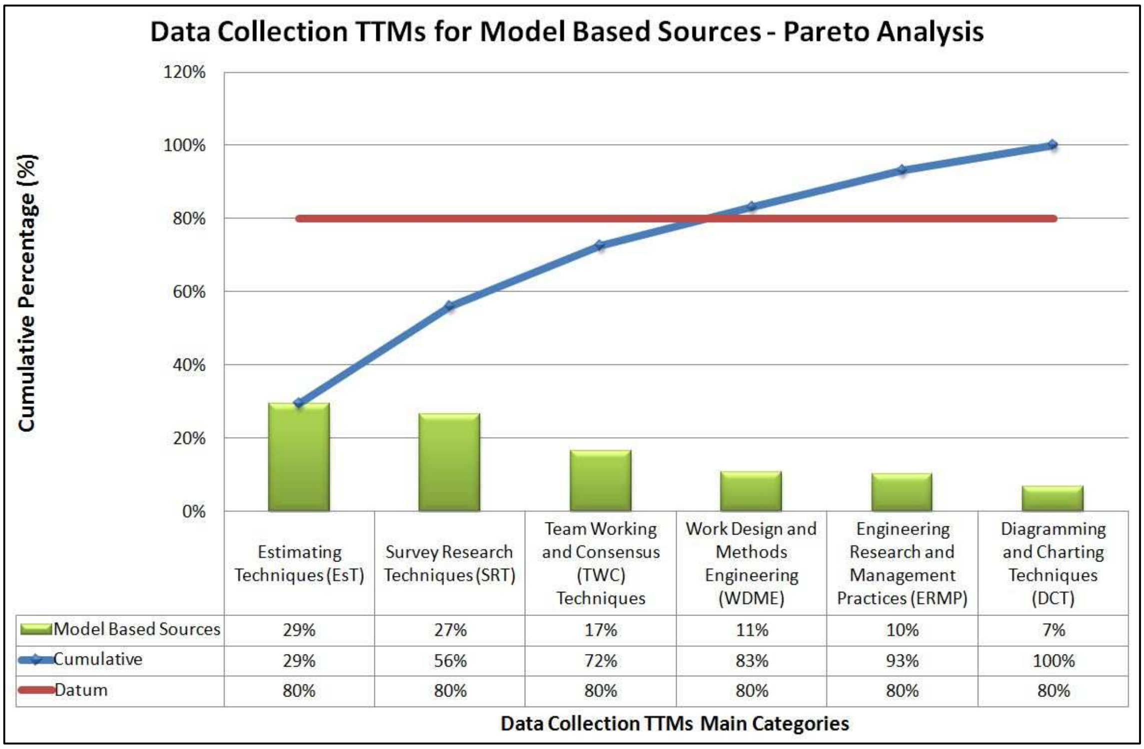


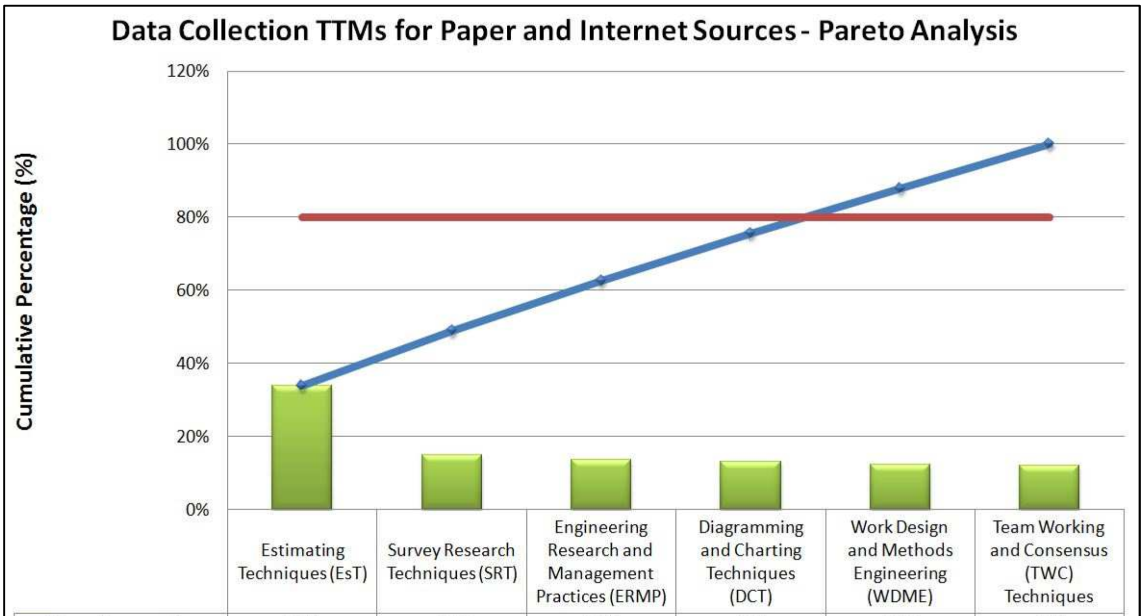
Figure 5.24 Data Collection TTMs for Model Based Sources – Main Categories

Brainstorming is a data collection and identification method for firsthand data which makes use of other data collection methods and techniques such as Affinity Diagrams, Paired Comparison, Consensus Building, Relationship Diagrams, Delphi Procedure, and Cause and Effect Diagrams for presenting and organising the data. It is felt that the experts taking part in the focus group activity may use the techniques intuitively, without using any structured approach.

Paper/Internet Based Sources

These sources concern literature reviews (desktop research) based upon electronic documentation produced from online resources (Internet and www) such as electronic Library Catalogues, subject specialised search engines and databases. Online professional discussion groups such as the AACEI Cost Estimating Committee and Cost Engineering Committee Forums and Special Interest Groups from Professional Institutions and Organisations are part of this category as well.

They also involve Departmental records such as manufacturing and accounting reports and data, for instance, labour cost rates. Operator's Black Book; Quality manuals and reports; Planning and Control Sheets; Shopfloor Documentation; Patents; Company and Industry guidelines and Recommended Practices fall also into this data source category.



	Estimating Techniques (EsT)	Survey Research Techniques (SRT)	Engineering Research and Management Practices (ERMP)	Diagramming and Charting Techniques (DCT)	Work Design and Methods Engineering (WDME)	Team Working and Consensus (TWC) Techniques
Paper/Internet Source	34%	15%	14%	13%	12%	12%
Cumulative	34%	49%	62%	76%	88%	100%
Datum	80%	80%	80%	80%	80%	80%

Figure 5.25 Data Collection TTMs for Model Based Sources – Main Categories

As shown in Figure 5.25, the category of data collection tools and techniques with the highest response was Estimating Techniques. The responses were almost equally spread among the different individual methods and techniques; namely, Analytical Estimating, Category Estimating, Comparative Estimating and Judgemental analysis technique.

It is important to consider the type of data the participants expect to obtain by researching into or looking up into the data sources previously mentioned in order to understand the rationale behind the decision making process that takes place when selecting the most appropriate data collection tool. For example, for a product or process in their concept stage, when there is not enough data available and knowledge on the process or product is scarce, data sources as the ones mentioned above seem to be a good starting point to begin with, especially when there are no similar products or processes available or related data.

As for the data collection tool, Analytical technique, for instance, is used most commonly in any work environment where a lengthy time (and associated high cost) is needed to collect data. Perhaps this is the most significant advantage of using analytical estimating: its speed of application and low cost. Using trained and experienced personnel, process and measurement data can be quickly identified, collected, assembled and applied; where it may be difficult and more expensive to collect the information required using other techniques.

Analytical estimating is basically a structured work measurement technique. The formal BSI definition states that it is an estimating technique, in which the time required to perform each constituent part of a task, work element or basic component operation, at a defined rate of working is estimated either from knowledge and practical experience of the work and/or from synthetic data.

Standard times, where available from another source, are applied to these work elements. Times are applied to the remainder, where no prior data are available, by estimating based on experience of the work under consideration. The estimation is carried out by a skilled and experienced operator who has had additional training in the process of estimating and who simply estimates the time that would be required during manufacturing by a fully competent and experienced operator, working at a predefined performance level.

Unfortunately, the work content of some tasks cannot be estimated in advance because one is unclear about what is required until an assembly operation has been tested or stripped down. The use of experienced judgement when determining the time necessary to perform a task becomes a valuable asset. Also, in some work environments the presence of an individual carrying out work measurement in the work place could be unacceptable. In these cases, analytical estimating may be an appropriate method to use, assuming someone with experience of the work is available to apply their experienced judgement. Consequently, experience and judgement are important elements of the technique in order to know what to look for when accessing the sources of information required to gather the necessary data.

Other tools and techniques identified include those under the category of Survey Research Techniques (SRT); Diagramming and Charting Techniques (DCT); Engineering Research and Management Practices (ERMP)

Heuristic Sources

As shown in Figure 5.26, Survey Research Techniques (SRT); Estimating Techniques (EsT); and Team Working and Consensus (TWC) Techniques were identified as the main data collection categories for sources such as Rules of Thumb, Personal Judgment; and experience and Expert opinion.

Interviews (as a survey technique) and the TWCs such as Brainstorming, Creative thought, and Decision modelling were identified by the respondents as the main data collection techniques to gather information coming from those heuristic sources. Comparative estimation from the EsT category, was the technique with the highest frequency of response.

Among all the data sources considered in the study, Heuristics were the category with the lowest response rate not only for this focus group exercise, but also when investigating the ability of data sources to provide information on data types at different levels of detail and product development stages. Work on the subject of eliciting information from experts has been carried out (Rush and Roy, 2001a and 2001b); however, it seems to be still scope for further investigation in the subject.

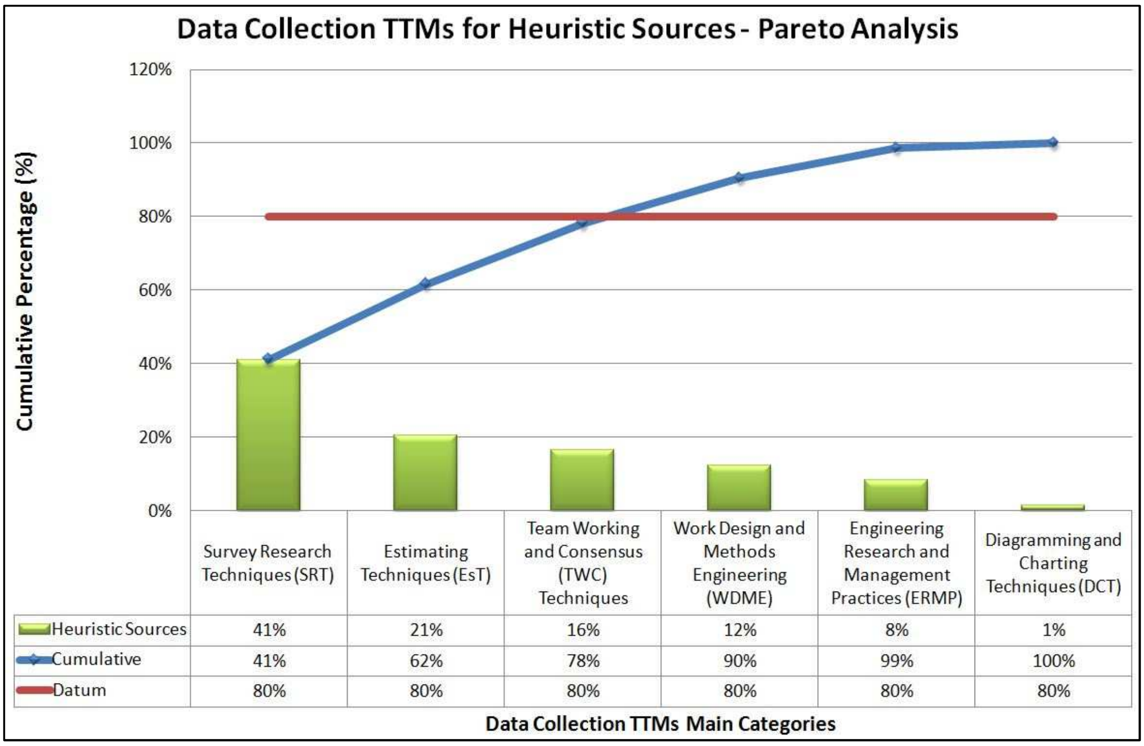


Figure 5.26 Data Collection TTMs for Model Based Sources – Main Categories

5.4 Selecting Input Data Types, DS and DC-TTMs in the CMDP

The aim of the research in this work area was to identify existing and potential data identification and data collection tools, techniques and methods used within the cost modelling process and to determine under which conditions each method was more appropriate for application; this is given particular data sources and data types to be able to select the most suitable tools, techniques and methods to conduct the data collection tasks. This aim was achieved through a couple of survey questionnaires, planned schedule of follow up visits and interviews to industrial participants and organisations and focus group exercises. The questionnaires, in conjunction with formal interviews with experienced cost engineers, enabled a thorough review of the current practices at these companies to be achieved.

There were identified particular preferences to use certain categories of data sources and collection methods. It was also revealed that, within the same category, there were differences in terms of the preference for certain data collection methods and sources of data.

In terms of data sources, Process and Product sources are the two most common providers of information. As expected, the primary and most important data sources identified were experienced cost engineers and manufacturing process experts.

Data sources falling into the categories of Model based and Synthetic sources are also well known and used among the costing engineers taking part in the focus group.

There is a predilection for the use of Estimating Techniques (EsT), followed by Survey Research Techniques (SRT) and Engineering Research and Management Practices (ERMP), as data collection methods. This is among the whole range of data source categories.

Some techniques such as Diagramming and Charting Techniques (DCT) and Team Working and Consensus (TWC) Techniques were expected to have better performance or received higher response among participants, in particular for data sources such as Product, Process Models and Heuristic sources. For Team Working and Consensus (TWC), these data collection methods and tools are primarily used at higher level of management or in functions such as Design and Development for identification of opinions, suggestions, ideas and collection of information in a structured and systematic way. Diagramming and Charting Techniques (DCT) are also of application at these functions, but also in production, planning and resource allocation activities for process and operation improvement initiatives. The extent and appropriateness of their use in cost modelling, in particular for data collection and identification tasks, however, it is still to be investigated and established.

5.5 Final Remarks

The work described is part of an Exploratory Sequential Multi-Method (ESMM) research investigation which looks into the data collection process used within the CMP for the generation of cost models. Extensive literature review was carried out, a couple of survey questionnaires were designed and applied, company visits and follow up interviews with experts in cost engineering and modelling conducted. The extensive literature review carried out ensured that knowledge of cost modelling processes and approaches was gained from both national and international sources. Three main themes were identified and selected for investigation; namely Cost Data Sources, Data Collection methods, tools and techniques and the Data Collection tasks in the Cost Modelling Process.

The research methodology included tools and techniques which relied, heavily or completely, on the input from experts either individually or as part of a team. Survey Questionnaires I and II, interviews for follow up, small group discussions, focus group for completing Relational Matrices for DC-TTMs, Data Types and DS identification were some of the research methods used in the Exploration and Formulation research stages. Later on in the investigation, during the Evaluation and Validation stages, case studies were also conducted.

Gathering information from the experts proved to be a challenging task, particularly when a group or team had to be assembled. For instance, surveys and group discussions for the identification of potential DC-TTMs and DS; focus group for testing and validating the PC method and the MSF. Furthermore, issues concerning confidentiality, competitive nature of the products and strategic sensitivity of the information around the subject of cost modelling and estimating all add to the challenge.

Despite the constraints, using the expertise and knowledge of professionals in the area of cost estimating, engineering and manufacturing revealed issues on the subject in a way no other research technique would have done it and enhanced the knowledge and understanding of the researcher on the subject beyond expectations.

The importance of adopting an effective CMD methodology has been discussed, along with the contribution of the cost modelling tasks of data identification and data collection to improve the development process of cost models, by providing the first steps to make it a ‘Leaner’ process.

Potential DS and a range of DC-TTMs for data gathering were identified and categorised. The findings from the analysis of the data entries into the DS-Dtype matrix and the DS-DC matrix were discussed at the category levels for both DS and DC-TTMs. Particular preferences were identified on the use of certain categories of DS and DC-TTMs. It was also revealed that there were differences in terms of the preference for certain DS and DC-TTMs, within the same category. New methods and tools are also gaining importance.

In order to identify DS and consequently potential DC-TTMs, it is a major requirement to identify the resource to be costed using the model and, therefore, the variables involved, previous to the start of the data collection tasks. Traditional CMD approaches lack structured methods or procedures for determining potential variables and deciding which ones should be used as input data to develop the model. For this reason cost model development approaches have to rely on the judgement and experience of cost engineers and on the knowledge of process and product experts. Current research focuses on developing tools and procedures to elicit information from these experts. However, this is only possible when existing manufacturing processes and products are considered and is unsuitable when new products and processes are being examined. In addition, such an approach usually results in unnecessary collection of redundant data. This situation creates waste in the process; that is wasted resources and added time required to develop a suitable cost model.

The Formulation stage of this research investigation confirmed that all variables within cost models, fall into three data types; namely, product features, process features, and process activities. Utilising a modified version of the PC method, and making direct use of the gained knowledge that only three data types are used as predictor variables within cost models, specifically product features, process features and process activities; a Library of data types was built using the manufacturing processes from the UK aerospace companies taking part in the research. The focus group exercise, participants' feedback and the analysis of the gathered data made possible to gain a deeper understanding on the nature and basic structure of cost drivers and to corroborate the claim that they are the result of different combinations of product features, process features, and process activities and not as previously assumed made by individual features or activities.

It has to be said that the relationship and attribute components of the PC tool did not assist as much as expected on the generation of the database. Their contribution on the identification of product features, process features and process activities is still to be explored.

This work has been the basis for the development of a CMP Methodology. It is expected that the proposed CMP Methodology will assist cost engineering practitioners in defining the features and activities of the process and the attributes of the product for which a cost model is required, and also in identifying the cost model characteristics. With these two set of information, namely, process and product information and cost model characteristics, it is expected that the cost practitioner will then be able to identify potential data sources and to select from a range of the DC-TTMs the most appropriate techniques for data gathering for the job on hands, in a more time efficient, visible and organised way.

The Methodology has been described in the subsequent chapter. The MSF tool developed as part of the CMD Methodology is also described and validated in Chapter 6.

CHAPTER 6. PROPOSED CMD METHODOLOGY AND THE MSF TOOL

6.1 Introduction

The importance of a structured CMD Methodology has been identified through the work carried out for this research investigation and particularly established by the literature review, and Questionnaires I and II.

This chapter describes the proposed CMD Methodology as well as the Model Assessment tool or Model Scoping Framework which form part of the proposed CMD Methodology.

The Chapter includes the validation, analysis and discussion of results of the CMD Methodology via a case study and the verification of the MSF and PC improvement tools, via industrial trials on existing and new models conducted at the industrial collaborators and participants in the research.

6.2 Proposed Cost Modelling Methodology

Current CMD procedures do not have ways or methods for determining the initial detailed specification of the cost model and the characteristics of the product and manufacturing processes for which cost models need developing. This research investigation proposes a CMD methodology which gives emphasis to the decision making process which involves:

- Identifying the model purpose and characteristics along with the product and process features and manufacturing process activities
- Selecting the data types that need collecting and the potential DC-TTMs to gather the necessary information in a timely and efficient manner and
- Highlighting contradictions between required cost model characteristics and evaluating the ability of the CMDP to achieve these characteristics.

The use of PC as a tool for the identification and ranking of product and process features and process activities along with the utilisation of Path Analysis diagramming for visual representation of the relationships between data types and their elements at different levels of detail, drew attention to the importance of the definition stage of the CMDP, specifically the data identification and collection steps within it. Along with the MSF, it showed that structure and planning before starting the data collection tasks is vital to avoid gathering unnecessary information, wasting resources and time. This was confirmed during the semi-structured interviews with cost engineering experts, following Questionnaires I and II, and from feedback gathered after the verification and validation exercises at participant companies.

6.2.1 Company Visits, Small Group Discussions and Interviews

The proposed Methodology for cost modelling originated from the combination of the literature review and Questionnaires I and II. It also takes into consideration best practices as identified from the COSTMOD project, NASA Cost Estimating Handbook (CEH), DoE and DoD Cost Estimating Guides, and the GAO's Cost Estimating Process, including the following:

- The initial purpose and scope definition stage adapted to suit the requirements of the manufacturing cost modelling process and cost model characteristics. To this end, a Model Scoping Assessment tool was developed to conduct the task of identifying the cost model purpose and characteristics as well as to establish the data requirements concerning the process and product features and associated activities. It also aims to clearly define ground rules and assumptions and what is included and excluded from the model.
- The product-oriented approach of the WBS of step 4 of the GAO's estimating process and the COSTMOD MIP (Model Identification Process) motivated the use of the PC Matrix and the Path Analysis method to investigate their suitability in identifying data cost elements (types and levels), define the logical relationship of the elements (independent/predictor variables) and weight their effect on the dependant variable defining the resource.
- The need to reduce lead times to produce the model without compromising the model's characteristics including its completeness, consistency and accuracy. Data sources, data types and DC-TTMs were identified and their links were established from Questionnaires (I and II), thorough literature review, and focus group exercises. Libraries of these elements were created to assist in the decision making process of the CMP data collection tasks and incorporated as part of the proposed Methodology, hence, aiming to reduce the lead time of the most time consuming task in the CMDP; that is data collection.

- The validation of the cost model which requires that they are well documented to the point at which they can be easily repeated or updated and can be traced to original sources through auditing. The documentation should be detailed enough to provide an accurate account of the model quality; therefore it should include among other things sources of the data used to generate each cost element, primary methods, calculations, results, rationales or assumptions. The documentation should also describe every CER for every cost element included in the model.
- The need to revise the model to keep it up-to-dated in order to reflect actual outputs and changes. To reflect its current status and check for accuracy, a thoroughly understanding of how the cost model was built is required. This includes all CERs being checked to verify that calculations are accurate and account for all costs and that appropriate currency conversion rates and escalation factors are considered. In addition, spreadsheet formulas and data input should be rechecked.

It also includes expert opinion and suggestions for improvement gathered from cost engineers at the participant companies. Notes taken by the researcher during semi-structured interviews and written documentation and communications (emails) provided by the engineers were the methods for data collection. Figure 6.1 below is an example.

To: Ysolina Arvelo
Subject: RE: Draft diagram for the Cost Model Development Process

Follow Up Flag: Follow up
Flag Status: Flagged

Hello Ysolina,

Had a look through the process you have described, only comments I would make would be as follows ;

- In the 'Scope the model' task, I would add that you would need to also scope the resource requirements to complete the model/project and the required timescales of the customer
- In the 'collect data' task, it may be a good idea to articulate that the sources of the data may be both internal and external to the company, which may have implications as to its ease of availability
- In accordance with our discussions, you have added the 'archive the model' task at the end of the process, there will also be a requirement to make certain models available on a central directory to be used by other value engineers, with some criteria being added to the model as to when it was created and what its potential duration of validation may be, i.e. when it may require to be updated

Hope this is useful

Regards

Neil M Keenan

Value Engineer - Materials Specialist
Value Improvement
Rolls-Royce Plc

Figure 6.1 Extract published with permission describing suggestions for improvement of the proposed CMD Methodology during its validation stage

After the feasibility of the suggestions for improvement were analysed and those considered appropriate were incorporated, a final model of the CMD Methodology and its steps was developed. Figures 6.2, 6.3 and 6.4 show an outline of the CMD Methodology being proposed.

A case study exercise was conducted to test the validity of the CMD Methodology. It was carried out at Rolls Royce plc at Derby. Company visits to the site took place to meet with cost engineers to discuss the potential suitability of the methodology. A product (Turbine Blade) was chosen to follow the CMD Methodology and a small group discussion took place focusing mostly on the initial steps of the CMD Methodology which involve the Model Definition and Data Identification and Collection stages which are the main focus of the research. The engineers provided their views based on their cost modelling experience and product knowledge. Once the appropriate changes for improvement were made a final evaluation of the CMD Methodology's outline took place for its final approval.

Due to constraints including time and resources available, the proposed CMD Methodology was only validated up to the point of identifying the Data Collection TTMs which was, in essence, one of the main objectives of the present research. It was not possible to measure and make comparisons of the current time and the new time (using the new CMD Methodology) to develop the model. However, there were other non-measurable benefits described by the participants, including providing a structured and coherent approach for developing cost models; allowing defining the model purpose in the early stage of the model development process, providing a common language and well defined stages and having the potential for shortening development times and for bringing cost models in line with the business objective they are developed for. Further work is still required to test the new proposed CMD Methodology to its full capacity.

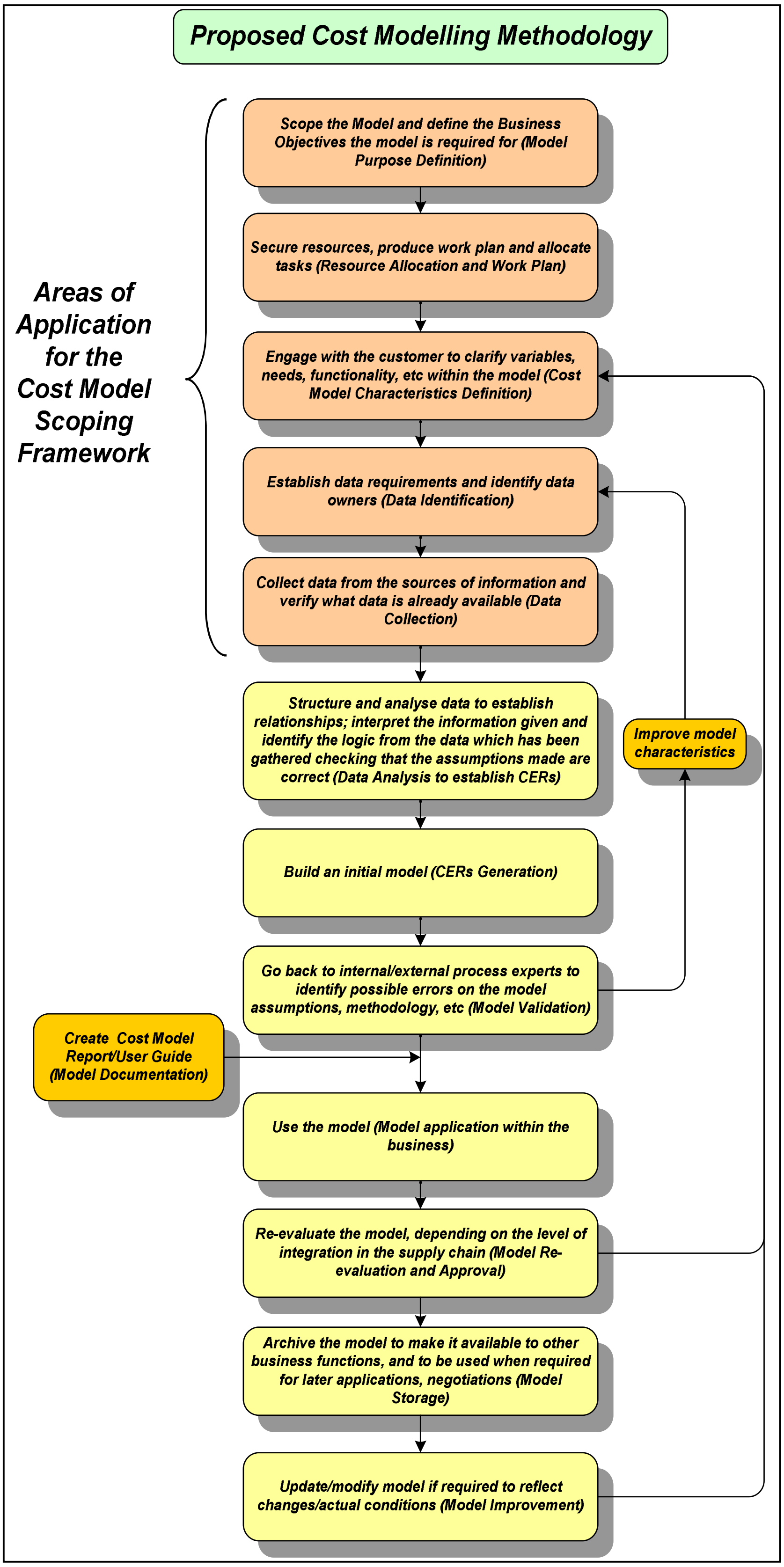


Figure 6.2 Outline of the CMD Methodology proposed (Developed Work)

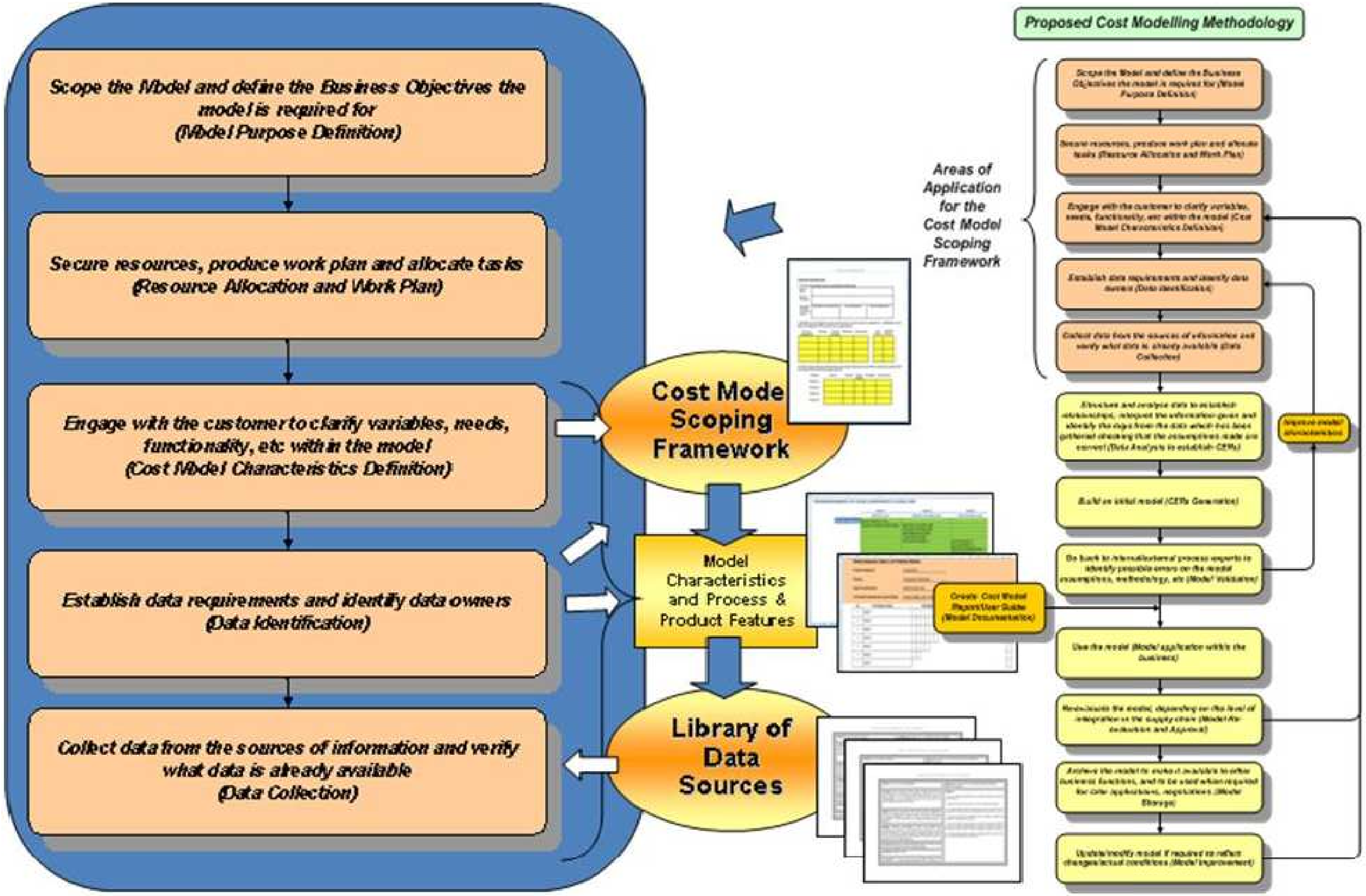


Figure 6.3 Cost Model Scoping Framework within the CMD Methodology proposed (Developed Work)

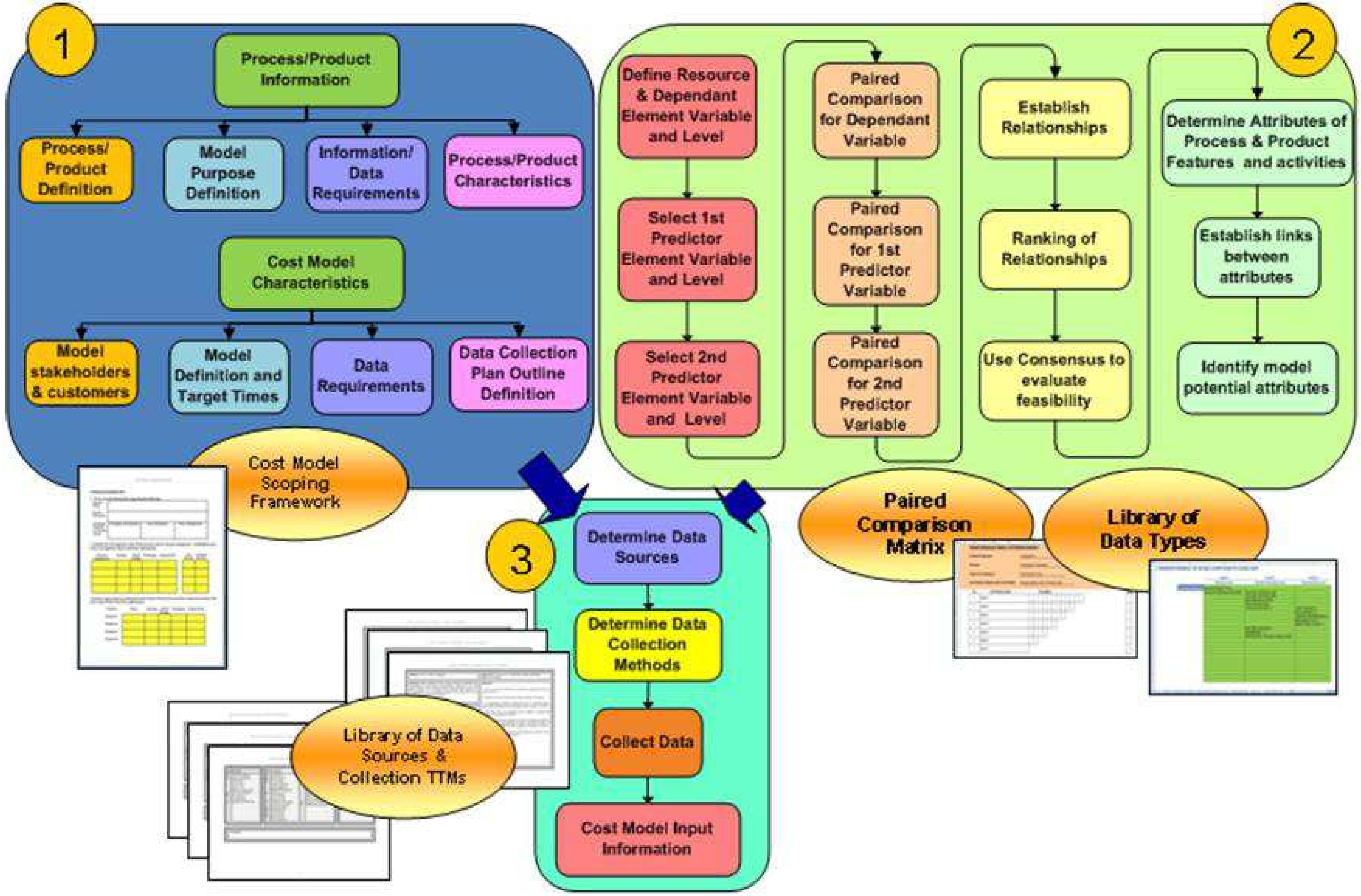


Figure 6.4 Steps involved in the Model Scoping Data Identification and Collection Stages of the proposed CMD Methodology (Developed Work)

6.2.2 Case Study 1: Engine Blade Manufacturing

Background Information:

On the Product:

The engine turbine blades, fan, and compressor blades are manufactured by Rolls Royce plc (RR) and the different components are assembled at one of their facilities.

On the Model:

The model required for this product was to be used as a pricing mechanism and to evaluate the 'change in cost' of introducing what was considered as a particular improvement measure within the manufacturing process in place. The output from the model was going to be utilised to agree on the price that RR was going to be charged by a particular (internal) supplier.

Open discussion took place and the following comments were made:

- "The methodology should consider the cost of acquiring the data, which is in close relationship with the time available to collect the information and the final model accuracy"
- "The methodology should take into account the product and process maturity"

It was explain by the researcher that the Model Scoping Framework built within the Development Methodology takes both of these factors into account when it asks for the definition of the product and process characteristics; particularly, data availability and resources, and the product/process characteristics.

Completion of the Model Scoping Framework: (Step 1 – Figure 6.4)

Following the discussion, the engineers were asked to complete the MSF form for the model and process characteristics and to identify the required data types and their levels. Validation examples of the MSF are described in section 6.4.2.

The cost elements or resources are the process activities, process features and product features at one of the three levels determined in the model scoping exercise. The model scoping also determines what generic cost types are to be used for the model. This should limit the data sources available for establishing the CERs. The resource to be costed for the case study was Product Cost (Turbine Blade); the dependant element was Product Feature at Level 1. Predictor elements (variable) included process activities and product features.

Completion of the Pair Comparison Matrix: (Step 2 – Figure 6.4)

On completion of the model scoping assessment tool, the Paired Comparison form was completed. The purpose of the PC method was to identify the cost elements and their attributes so that the potential data sources and data collection tools, techniques and methods could be identified.

The Path Analysis Diagram resulting from the PC exercise for the Turbine Blade, as described by the engineers, is shown in Figure 6.5. The data types for the Turbine Blade were incorporated into the Data Library for Product and Process Features and Process Activities (Figure 6.6). The PC process was previously used (and its suitability verified) for the identification of product and process features and process activities for building the Data Types' Library, when testing the suitability of the data types' Taxonomy (in Chapter 5).

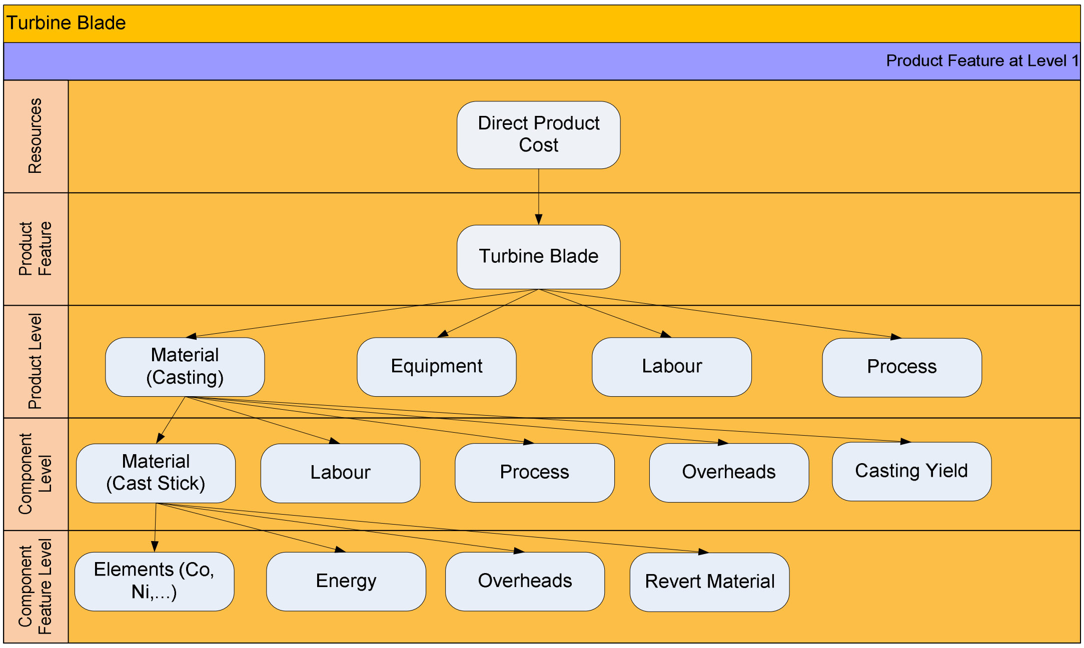
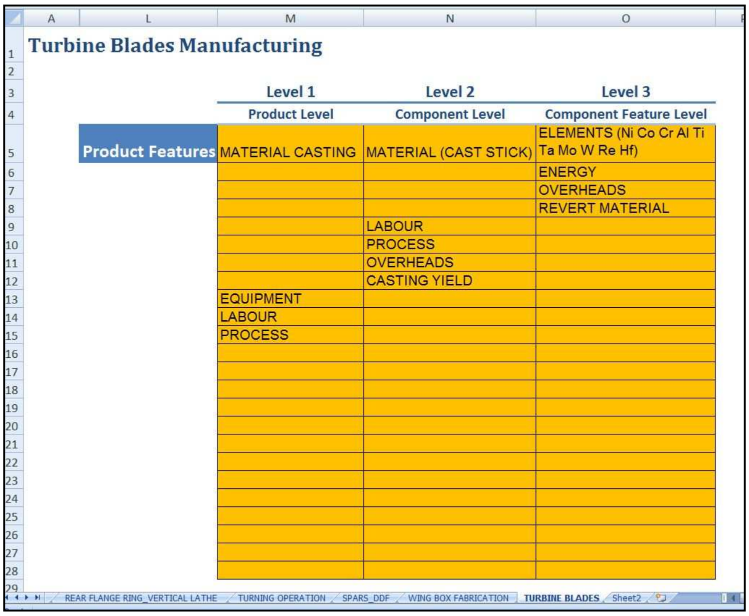


Figure 6.5 Path Analysis Diagram – Data Types for Turbine Blade Cost Model (Developed Work)



Turbine Blades Manufacturing

	Level 1	Level 2	Level 3
	Product Level	Component Level	Component Feature Level
Product Features	MATERIAL CASTING	MATERIAL (CAST STICK)	ELEMENTS (Ni Co Cr Al Ti Ta Mo W Re Hf)
			ENERGY
			OVERHEADS
			REVERT MATERIAL
		LABOUR	
		PROCESS	
		OVERHEADS	
		CASTING YIELD	
	EQUIPMENT		
	LABOUR		
	PROCESS		

Figure 6.6 Turbine Blades Manufacturing - Data Library for Product and Process Features and Process Activities (Developed Work)

Identification of Data Sources and Data Collection TTMs: (Step 3 – Figure 6.4)

Once the data types were identified and their relationships were established, the participants used this information and the information collated using the Cost Model Scoping Framework to refer to the Library of DS and DC-TTMs to select the most suitable data collection tools to carry out the data collection tasks. All the process was carried out manually.

As shown in Figure 6.7, Material (Casting) was defined as the Dependant element at Level 1 (Product Feature). Product features at Level 1 for Material (Casting) can be product design features and material specifications. It has to be pointed out that this is not an exhaustive list and new entries can be added.

A. Data Form		Data Type	Tick as appropriate
a	activity descriptions	process activity	
b	activity times	process activity	
c	manpower requirements	process activity	
d	activity dependencies	process activity	
e	task sequences	process activity	
f	operator's motion patterns	process activity	
g	resource descriptions	process feature	
h	resource times	process feature	
i	resource costs	process feature	
j	accounting data	process feature	
k	equipment operating data	process feature	
l	cost rates	process feature	
m	process description	process feature	
n	product design features	product features	✓
o	Material specs	product features	✓

C. Potential Data Sources			
✓	actual process	✓	departmental records
✓	video of process	✓	CAD files
✓	process expert		operator's 'black book'
	synthetic standards	✓	quality manuals/reports
✓	costed components	✓	equipment performance
	standard PTMS systems	✓	product specifications
✓	similar processes	✓	engineering drawings
	creative thought		empirical laws
✓	literature reviews		process controllers
✓	equipment specifications		planning & control systems
	maintenance manuals		shopfloor documentation
	operating manuals		
	training manuals		
	process models		
	physical models		
	CNC programmes		

Figure 6.7 Potential Data Types and Data Sources identified - Turbine Blade Cost Model

For those data forms, the potential data sources identified included sources from the process (actual process, video of process, similar processes, process expert); product (costed components, product specifications, engineering drawings, CAD files); paper-based and internet sources (quality manuals and reports, departmental records, literature reviews) and equipment sources (equipment specification and performance records). According to the results from the Pareto analysis in Chapter 5 (DS Categories versus DC-TTMs) the DC categories most suitable for those sources are listed in Table 6.1.

Samples of the information on potential DC-TTMs found using the DS-DC Library are shown in Figures 6.8 to 6.10. The decision making process as to what DC-TTMs would be most suitable for data gathering will be driven by the characteristics of the cost model and process/product under consideration as established during the model scoping exercise. The next section describes the validation of the MSF.

From the case study exercise it seems that the CMD Methodology does not offer any difficulty in terms of understanding what is involved at each step. Nevertheless, completing the MSF and the PC Matrix for the Turbine Blade model was another matter. The participants had to be talked through the forms which may suggest that further consideration may be required. One possible solution may be to attach a rationale to the forms (including examples) in addition to the instructions for completion.

Moreover, investigating the suitability of alternative techniques such as AHP should be seen as future work.

DC-TTM	Process Sources	Product Sources	Paper-based & Internet Sources	Equipment Sources
Estimating Techniques (EsT)	✓	✓	✓	✓
Survey Research Techniques (SRT)	✓	✓	✓	✓
Team Working and Consensus (TWC) Techniques	✓			
Work Design and Methods Engineering (WDME)				
Engineering Research and Management Practices (ERMP)	✓	✓	✓	✓
Diagramming and Charting Techniques (DCT)			✓	

Table 6.1 Potential Data Collection Categories for the identified Data Sources for Material Data - Turbine Blade Cost Model

Data Collection Techniques, Tools and Methods

Method: Judgmental analysis technique

References: Gerald Nadler, Work Design - A Systems concept, Richard D. Irwin, pp.193-204
ISBN 085012
LCCC No 7011417

Function: To collect data from a panel of experts and so to generate an equation or representation of a joint policy.

Inputs: Alternatives on which data must be collected, a measure of the alternative, scores on the alternatives from the panel of experts.

Outputs: A ranked order of alternatives that are used as well as the information concerning the alternatives to produce a set of prediction equations and a final "prediction" equation.

Personnel: Concurrent engineering or product teams for example with manufacturing experience, who have been trained to use the judgmental analysis technique.

Equipment: Paper, pencil, set cards or PC based software used to automate the process.

Environment: Judgmental analysis may be used in any environment where work is undertaken, eg manufacturing, distribution, office

Sequence:

1. Decide on the alternatives that data collected about them.
2. Record the alternative upon a card as well as further information that is felt relevant.
3. Decide on measures of the alternatives.
4. Place a score, say on a scale of (1-9), and ask the experts to place the scores on the corresponding cards.
5. Each expert, using his judgement, places the cards in an order corresponding to a chosen criteria.
6. Use each alternative or the information as a predictor variable and the ranking of alternatives as a criterion variable.
7. Generate a set of regression equations.
8. Aggregate the equations together to form a representative equation.

Figure 6.8 Judgemental Analysis Technique (EsT Category)

Data Collection Techniques, Tools and Methods

Method: Operational Experimentation

References: Gerald Nadler, Work Design - A Systems concept, Richard D. Irwin, INC.pp 194
ISBN 085012
LCCC No 7011417

Function: To examine a factor or phenomena within a manufacturing process and being able to establish its magnitude. Carried out within the controlled environment of the laboratory.

Inputs: Production rate, machine speed, operating or experimental quality

Outputs: Measurement of the factor or phenomena to be investigated. From these results data analysis will establish if there is a relationship of any significance.

Personnel: Requires an Engineer who has a good understanding of experimental procedure.

Equipment: Paper, pencil, PC and Excel or other statistical package.

Environment: May be used in most environments dependent on suitability for experimentation within a manufacturing facility.

Sequence:

1. Decide on what factor is to be investigated.

2. Determine what the standard amount of the phenomena is and what this represents.

3. Design experiment to investigate the factor for predetermined sets of settings. Also set up the measurement system that will collect the experimental data. Set up the data management system with appropriate data storage facility. This may be done using SCADA based data collection based systems.

4. Conduct experiment as specified above recording trial and taken note of any unexpected phenomena that occur.

5. Analysing the experimental results with the actual measurements being compared against the standard, leads to a correlation of the cost against a product feature or process feature.

Figure 6.9 Operational Experiments (ERMP Category)

Data Collection Techniques, Tools and Methods

Method: Interview

References: Oppenheim, A N (1992). Questionnaire Design, Interviewing and Attitude Measurement. Pinter Publishers, London. ISBN 1 85567 043 7

Function: Technique uses for collecting information/data by conducting, either a face to face or via telephone, formal and structured conversation or discussion with the person or group of people identified as the information source.

Inputs: The range and type of information or data that can be collected, depends on the objectives/purposes of the study and the level of detail required.

Outputs: General or detailed information and data regarding the elements (tasks activities, operations, resources, etc) necessary for the completion of the task, process description, description of the task and sequence of the activities involved, etc.

Personnel: It requires interpersonal skills of a high order.

Equipment: Paper, pencil, video recording equipment, audio (tape) recording equipment, PC, statistical tools to analyse the data gathered.

Environment: It may be used in any environment where work is undertaken, e g manufacturing, distribution, office, warehousing, etc. It is also applicable for market research, government surveys, public opinion polls, etc

Sequence:
1. Define the objectives and purpose of the study, in order to establish the kind of questions and level of detail of the information to be gather.
2. It has to involve those who do the work and/or supervise the process and the people who conduct the study.
3. Interview can vary from a rather formal and structured approach to completely informal and unstructured (similar to a discussion).
4. Formal interviews ask predetermined fixed, open-ended, or fixed-alternative questions, which standardised information. Unstructured interviews have great flexibility, which often provides significant insights through spontaneity of answers.
5. In most cases, interviews are a combination of the formal and informal approach using certain predetermined guide questions.
6. Interviews can be conducted individually or in groups.
7. Put the respondent at ease, and ask questions in an interested manner.
8. Note down the responses without upsetting the conversational flow, giving support without introducing bias. Prepare a hidden agenda, as guidance.
9. Organise, analyse and structure the gathered data and information, once it has been collected.

Figure 6.10 Interview Technique (SRT Category)

Other issues encountered during the activity included the interpretation by each individual of the different levels of detail of the data elements, and also agreeing on where to 'allocate' the various product and process data features and process activities. At the end, it was agreed by consensus to concentrate on only one product feature; namely, the material (casting) to carry out the PC exercise (Figure 6.5). It was also observed during the activity that it was necessary to go to the next level down in the Path Analysis Diagram. Although information at level 1 was supposed to be identified, it happened that the only way to find it was to move to the next level down. For example, following the Path Analysis Diagram in Figure 6.5, information on the process and properties (such as casting yield) of the material were located at the component level and even at the component feature level (for instance, composition elements).

The Methodology could not be validated in full during the case study. This would have included collecting the data, building the CERs, validating them and applying them within the business. Time and resource constraints were the main issues. However, consulted experts from the participant organisations are convinced of its soundness and especially give notice of its practical and realistic approach, as confirmed from the feedback gathered after the verification and validation exercises at the participating companies. Comments included:

- Structured and coherent approach for developing cost models… as the situation is right now, everybody develops models using their own expertise and methodology and knowledge goes with them when they leave the organisation…
- Incorporates the concept of model purpose definition in the early stage of the model development process this helps to stay focused and to get rid of unnecessary information and data
- It is an efficient approach as it has the potential to shorter development times and it is effective because places the cost model in line with the business objective the model is developed for
- Provides a common language and well defined stages throughout the whole process

Further research as part of future work could include validating the proposed new CMD Methodology in full. Chapter 7 discuss further work on this matter.

6.3 Importance of a Structured MSF in the CMDP

The Model Scoping Framework is a communication device created to assist the cost model developer in the process of making an informed decision regarding the development of the cost model.

This tool can be very helpful to staff and personnel assigned to input the process or product knowledge the cost model is developed for, as well as to cost engineering and estimating practitioners responsible for developing cost models. It aims to compile information related to a particular manufacturing process as well as information for establishing the characteristics of the cost model to be developed for the process or product under consideration.

The Framework also aims to establish links between the developmental state of the process or product being cost modelled, the relative volume of production, type of business objectives to be achieved and strategic, tactical or operational decision making levels under consideration with the appropriate cost model characteristics in terms of estimating accuracy, time available for developing the model, the resources available and the level of cost data required.

The scoping exercise takes place at the early (definition) stage of the CMDP (Figure 6.3) and aims to define the function of the process, and to estimate how much data is available, in order to assess the amount of effort required for developing the model. The next section provides a comprehensive discussion on the tool and its application.

6.3.1 Proposed Model Scoping Framework

Research carried out in the construction industry has acknowledged that appropriate project scope definition is a vital component for achieving good estimates (Serpell, 2004 and 2010; Trost and Oberlender, 2003). This principle also applies to cost models, which represent an important component required to construct estimates. Without an appropriate definition of the scope of the model, it is difficult to know the development time, effort (man-hours), model purpose (Business Objectives the model serves) and other cost model characteristics.

The CMP Methodology and the MSF presented in this work have evolved through a combination of literature review, focus group exercises, interviews, and the two survey questionnaires. The proposed MSF tool has been created to fulfil the following objectives within the Model Definition stage of the CMD methodology:

- Standardise on model development plans, strategy or procedures
- Reduce (optimise) time required to create plan for developing the model
- Increase accuracy
- Promote more effective use of resources and prioritisation of tasks
- Lay the foundations for the planning of the data identification and collection tasks and the definition of the predictor variables for the process resource to be costed.

The MSF was developed and verified using manufacturing processes and products at different development stages. It is used to gather information related to the manufacturing process which the development of a cost model is required as well as for information necessary to determine the cost model characteristics.

The tool provides primarily a process/product analysis tool, but it can also be used as an initial approach for the development of a process/product cost model, and as instrument for setting the performance measures to assess the cost model characteristics; namely, the model's estimating accuracy, level of detail of output data, and level of experience required to use the model and finally, the CMDP in terms of efficiency and effectiveness.

Each element of data contained in the MSF (Table 6.2) ought to be employed in the establishment of the cost models characteristics as they are the starting point for identifying and defining the assumptions and rules ('advice and contradiction rules') which constitute one of the basic elements for the development of the cost model.

The MSF document consists of two well-defined parts, each dealing with different but related objectives. The first section (Figure 6.11) concerns the information requirements for the manufacturing process or product under consideration. It includes the function of the process and development stage, type of processing system, main products involved, and working environment. The process or product information is used to establish the cost model characteristics, and to assist later stages in the cost modelling process.

The second section of the MSF (Figure 6.12) is related to the identification of the cost model characteristics in terms of function/purpose of the model; business objectives and decision making levels; accuracy and resources to be costed; time available and manning levels required to develop the model. This second part of the MSF, also includes the identification of basic business objectives and decisions levels, which the cost model or estimate is required to assist. The objective at this stage is to ensure that the appropriate levels of cost data are identified, and that the resources under consideration are estimated at the required level of detail for the decision making process they are expected to support.

Using this framework, the cost model developer should be able to answer the following questions:

- Is the purpose of the cost model clearly defined?
- Is the scope of the model clearly defined?
- Is the level of detail of the model and other pre-established characteristics consistent with the level of detail of the available data (data types)?
- Are the time and resources allotted to develop the model adequate?

The models discussed in the cost modelling specific literature seem to have overlooked this type of analysis. Too much emphasis is placed on the application and benefits of artificial intelligence methods for the analysis of cost data, while little attention has been given to the data collection steps for building the cost estimating relationships and the subsequent validation of the cost modelling process.

	Cost Model Characteristics to be affected				Cost Model Development Stages to be assisted			
PROCESS CHARACTERISTICS	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
Process Name and Function.					✓			✓
Volume of Production (i.e. Low volume, One-off, Medium Volume, High Volume).		✓		✓	✓			✓
Development State of the Process (i.e. Concept, Detail Design, Prototype, Commercial).	✓	✓		✓	✓			✓
Type of Production Process (i.e. Project, Job shop, Batch, Flow).		✓		✓	✓			✓
Identification of Process Experts (e.g. Machine Operator, Design team).	✓				✓			✓
Main Products involved.	✓				✓			✓
MODEL CHARACTERISTICS								
Function of the model.		✓	✓	✓	✓	✓	✓	✓
Business Objectives & Decision Levels.			✓	✓	✓	✓	✓	
Estimated Accuracy.		✓	✓	✓	✓			✓
Product & Process Resources to be costed/estimated.	✓	✓	✓	✓	✓	✓		✓
Time available and Manning Levels (Human Resources) required for: ➢ Collecting data ➢ Building the Cost Model ➢ Input data into the model ➢ Cost Model Life Span		✓	✓	✓	✓			✓

Key:

Cost Model Characteristics to be affected:

- A_1 Availability of Data (Data Sources)
- A_2 Level of detail of input data
- A_3 Level of detail of output data (final estimate)
- A_4 Model Accuracy

Cost Model Development Stages to be assisted (with the provision if this information):

- B_1 Background for preparing the Model Identification Process exercise.
- B_2 Identification of resources to be costed.
- B_3 Function of the Cost Model, i.e.:
  - To enable the estimation of element values (quantities models), e.g. process time based cost models (hours, man/hours, etc)
  - To enable the estimation of functional values or rates models.
- B_4 Selection of Data Sources & Data Collection tools.

Table 6.2 Cost Model Characteristics to be established during the Cost Model Scoping Exercise (Developed Work)

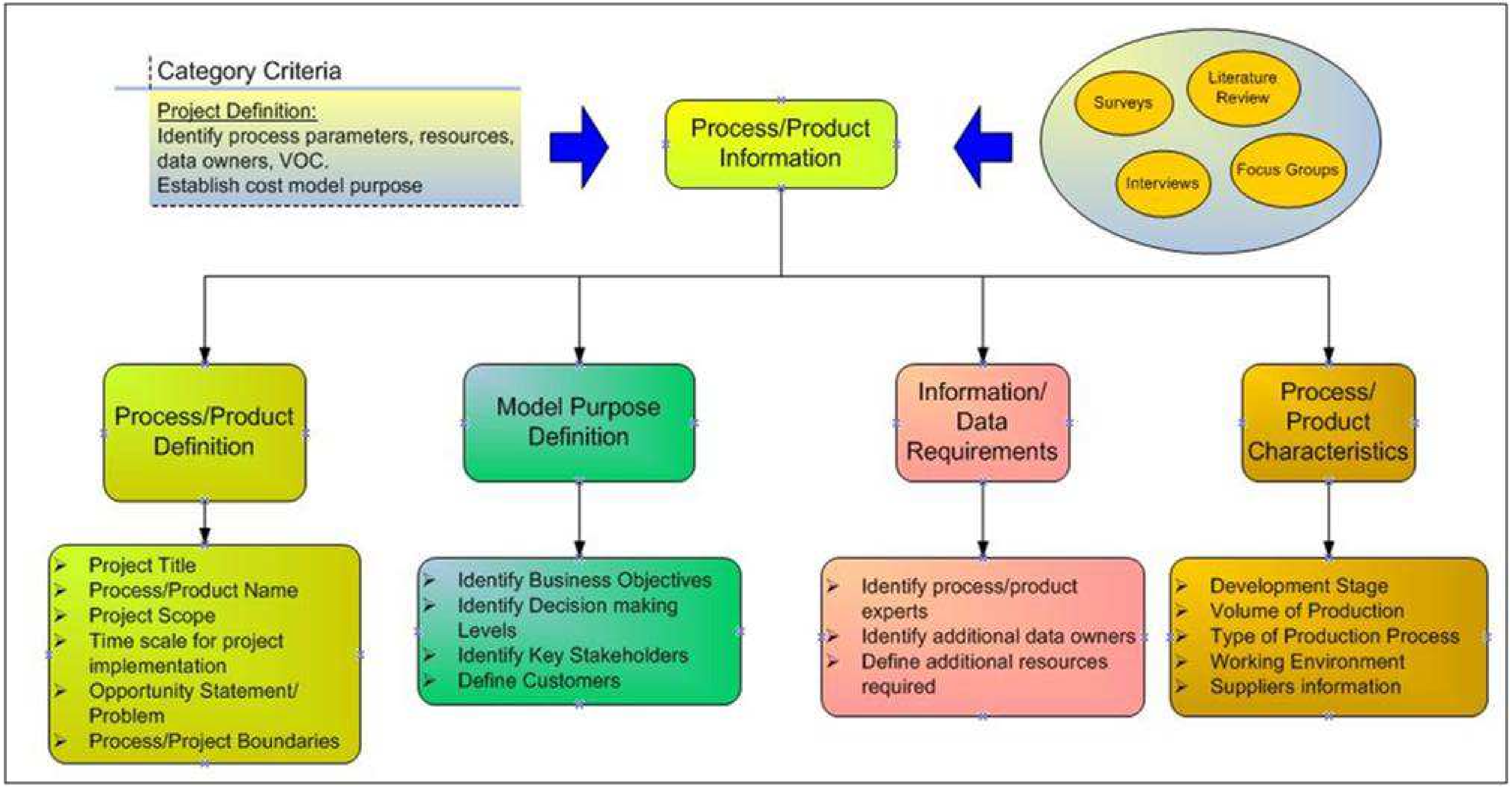


Figure 6.11 Cost Model Scoping Framework (CMSF) Part I: Process/Product Information (Developed Work)

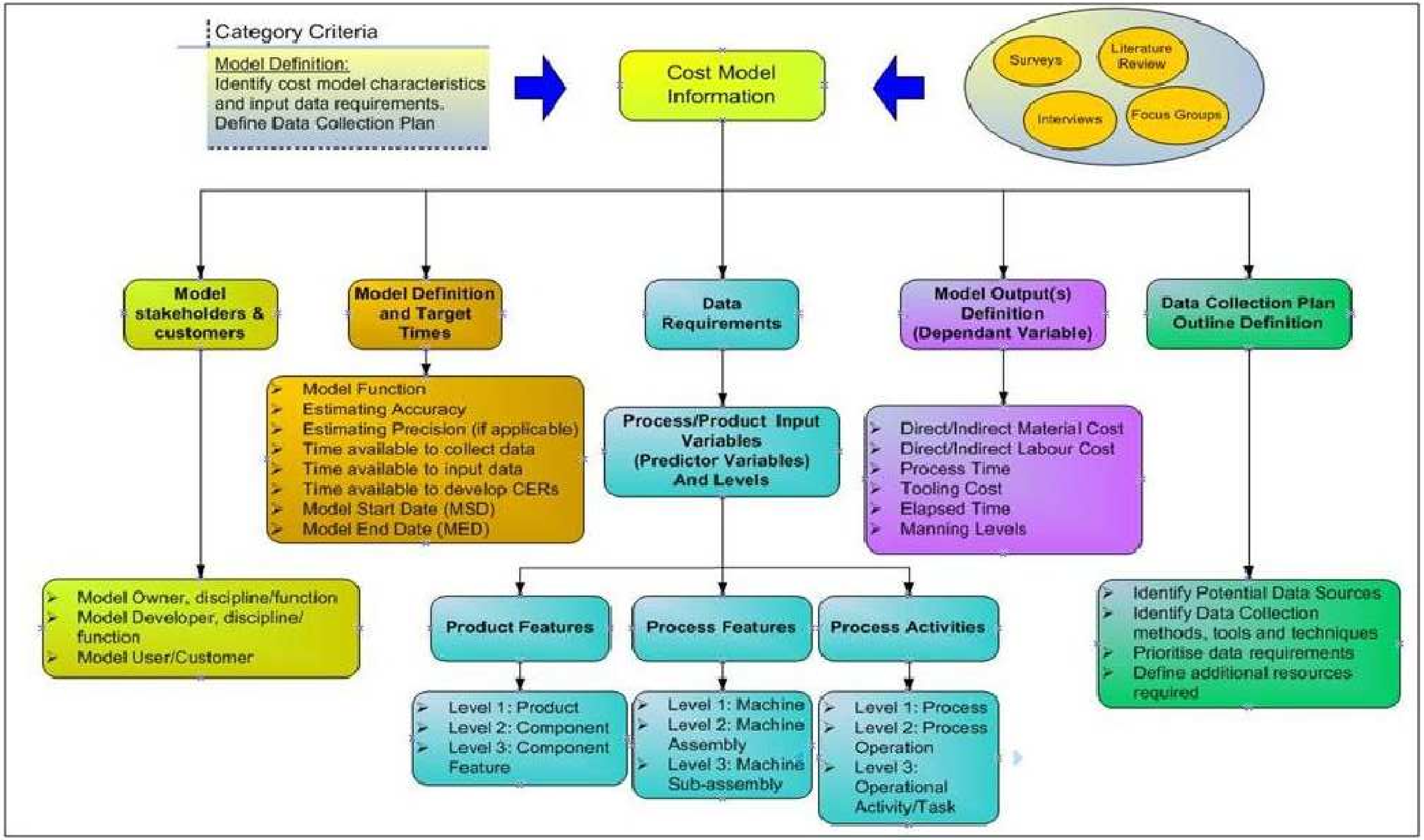


Figure 6.12 Cost Model Scoping Framework (CMSF) Part II: Model Information (Developed Work)

The following sections describe more completely this assessment tool.

6.3.1.1 Manufacturing Process or Product Information

This is the manufacturing process or product for which a cost model is required and its characteristics. It could be the whole manufacturing or assembly operation or a step of the process. In the case of the product, it could be the final product or a component or sub-assembly. The main sections include:

Process Name: Suitable name that shall describe the process or draw similarities from similar process

Process Function: what the individual tasks within the process are to achieve. For instance, metal removal, forming, fastening, treatments, handling and assembly. Measures of process function and efficiency need establishing.

Process or Product Development State: four basic product development stages are included:

- Concept: generalised idea or notion of the product/component, involves establishment of the functions to be included in the design, and identification and development of suitable solutions
- Detail Design: the individual parts of the product/component are defined fully to achieve their function and the dimensions, tolerances, materials and form of individual components of the design are specified in detail for subsequent manufacture
- Prototype: the first full size functional product/component to be assessed against initial concept functions
- Commercial: when the product is available for use in the market place

Volume of Production: it involves three levels: High Volume, Medium/Low Volume and Small Volume/One Off

Type of Production Process: four production types are considered. This classification is based on the main types of production process available in manufacturing. Depending on the industry, different production categories may be needed.

- Flow process: systems where one product/component passes through resources one at a time, with no buffer stock present
- Batch Production: it refers to the lot size of identical parts produced in a factory. This is the method adopted when the required product volumes are not adequate to permit continuous product of one product on dedicated machines. Once a batch of one product is made, the facility is changed over to produce a batch of the next product.
- Job shop: manufacturing businesses devoted to producing special or custom made parts or products, usually in small quantities for specific customers
- Project: it involves large variety of products that can be produced, for very low volumes or one-offs

Information about working environment, process boundaries as well as process data sources and information owners (manufacturing engineers, industrial engineers, design engineers among others) is also requested in this section.

6.3.1.2 Model Information

Business Objectives and Decision Making Levels: the purpose of the model should be aligned with the business objectives of the organisation in order to achieve its expected end. There are a number of business objectives a model may be intended to fulfil at different levels: strategic, tactical and operational. Changes in business objectives may require the model to be modified or improved in order to reflect those changes.

Cost Model Developers, Owners and Users: Practitioners in the area of engineering cost estimating come from a variety of backgrounds ranking from manufacturing and service industries, to construction and government. It is not uncommon that the model is produced to be used by a variety of purposes by people at different levels of management and from different business functions. Model owner is the department/personnel who will have control over the cost model, supplying the model to the user. Model Developer implies the personnel who will create the cost model.

Model Function: purpose of the model.

***Time Scale*:** includes the development time and operating costs associated with the model such as the time available to collect the necessary input data; time available to input the data into the model; when the model needs to be ready to use and for how long it will be used (Model life span).

Manning Levels: tasks involved in the data identification, data collection, and data handling and analysis are very time consuming but also very labour intensive depending on the amount of data to be collected. Those tasks must be completed in an effective and efficient manner before any input into the model takes place.

Product and Process Resources and level of Cost Data: detailed description of the items included in this section has been provided in previous Chapters and discussions. This includes the input data requirements for the model.

6.3.2 Validating the Model Scoping Framework

Once again, Case study research was chosen given the need to gather in-depth, rich data on the application of the MSF. Justification for this research approach being used for this purpose is given by authors such as Hussey and Hussey (1997).

The verification and validation process was conducted throughout a series of company visits (Table 6.3) and face to face interviews. Staff from the Manufacturing and Cost Estimating Functions at the participant companies reviewed the content of the MSF. Modifications to the original document were made accordingly. During the visits structured interviews were carried out to complete the paper-based version form of the MSF on selected process and product suggested by the companies taking part in the study. Following the exercise feedback on the process was provided by the model and process owners on its suitability.

Because of the repetitive nature of the process for testing the validity of the proposed CMD Methodology and its tools (MSF and PC Matrix) as well as the commercially sensitive character of the data and information being used for this purpose, only one case study is described fully; namely the Double Diaphragm Forming (DDF) for testing the MSF, which is the process at the concept stage of development. As for the other two processes, copies of the complete MSF exercises have been provided in Appendices D2 and D3, omitting confidentially bound information.

Company	Process Name	Lifecycle Development Stage
Rolls Royce plc (Derby and Filton sites)	Rear Flange (O-rings) Manufacturing	Commercial
BAE Systems, Military & Aerostructures (Preston site)	5 axes CNC Machine Station	Prototype
BAE Systems, Airbus (Filton site)	Double Diaphragm Forming (DDF)	Concept

Table 6.3 Processes used to validate the Model Scoping Framework

6.3.2.1 Case Study 2: Double Diaphragm Forming (DDF)

Background Information:

On the Product:

As previously agreed, the Process to be modelled was called Double Diaphragm Forming (DDF), if implemented it was going to be used for the manufacturing of wing components (spars). This process was currently under study at BAE Systems, Airbus at the time of the case study exercise. Therefore, process was in its concept stage.

This exercise allowed identifying the gaps in the data and cost information required as well as identifying the lack of knowledge on the process as it was in the concept stage. The MSF also helped to identify alternative ways of generating cost information when there was none available as first hand data, and potential DC-TTMs as alternatives to those already available.

On the Model:

The engineer in charge of the development and implementation of the model of the process was [redacted] (RA), Cost Engineer for the Composite Wing Program. He was the contact person for all matters regarding the process and provided the necessary information and data to build the model. Technical data regarding the process was also available from [redacted] (MD) and [redacted] (MR). The two main tasks involved were the Diaphragm Preparation and the Manufacture of the Component. A high level of detail was required, as the model was going to be used as a trade-off tool. Therefore it was necessary to capture all detail possible, concerning the recurring cost aspects of the process. Tooling, however, was excluded for this model. The estimate cost for tooling might be obtained from previous in-house cost exercises or obtained from external suppliers if required (external estimates). Detail at a main tasks level (for instance, load/unload laminated) is what was required from the model.

Completion of the Model Scoping Framework: (see Step 1 – Figure 6.4)

A complete MSF form has been included in Appendix D1.

Completion of the Pair Comparison Matrix: (see Step 2 – Figure 6.4)

The PC Matrix was completed for the DDF process and the identified process and product features added to the Library of Data Types (process and product features and process activities).

Identification of Data Sources and Data Collection TTMs: (see Step 3 – Figure 6.4)

As done before (Case Study 1), once the data types were identified and their relationships were established, the participants used the information from the PC exercise and the information collated using the MSF to refer to the Library of DS and DC-TTMs and selected the most suitable data collection tools to carry out the data collection tasks. All the process was carried out manually.

As a result of the exercise, a list of data sources on the process was generated (Figure 6.13).

A. Data Form		Data Type	Tick as appropriate
a	activity descriptions	process activity	✓
b	activity times	process activity	✓
c	manpower requirements	process activity	✓
d	activity dependencies	process activity	✓
e	task sequences	process activity	✓
f	operator's motion patterns	process activity	
g	resource descriptions	process feature	
h	resource times	process feature	
i	resource costs	process feature	
j	accounting data	process feature	
k	equipment operating data	process feature	✓
l	cost rates	process feature	
m	process description	process feature	✓
n	product design features	product features	✓
o	Material specs	product features	✓

C. Potential Data Sources			
✓	actual process		departmental records
	video of process		CAD files
✓	process expert		operator's 'black book'
	synthetic standards		quality manuals/reports
	costed components		equipment performance
	standard PTMS systems	✓	product specifications
✓	similar processes	✓	engineering drawings
✓	creative thought	✓	empirical laws
✓	literature reviews	✓	process controllers
✓	equipment specifications		planning & control systems
	maintenance manuals		shopfloor documentation
	operating manuals	✓	Patents
	training manuals	✓	Internet (www)
✓	process models	✓	Expert Opinion/Judgement
	physical models		
	CNC programmes		

Figure 6.13 Potential Data Types and Data Sources identified - DDF Cost Model

During the development of the cost model for the DDF process selecting appropriate data identification and collection methods was going to be necessary. The information available in terms of process times was based on trials done at a laboratory scale. There was not data available at the production level (such as Departmental records, CAD files, Costed components, Operating manuals, Operator’s 'black book', Quality manuals/reports, Equipment performance, or Shopfloor documentation), because the process had not been implemented yet.

It was felt by the participants that it was going to be very difficult to analyse all data related to the process, without a full understanding and knowledge of the process, as there was some information that was not relevant, but brought into the discussion. It was suggested that for processes such as this one, copies of all relevant information on the process/product to be distributed in advance before the model scoping exercise and the identification of the features and activities took place. For instance, copies of the Process Mapping for the DDF, the list of equipment to be used, and a copy of the Manufacturing Introduction Sheet were available.

Full understanding of the process for analysing and identifying the relevant process data, as well as a fluent understanding of the technical terminology used, along with the necessary information to build the model were considered paramount. These required working closely with the process expert in filtering all irrelevant data.

It was mentioned that some already available sources of data and information, such as the Internet, other companies and competitors’ reports (GKN Report), brochures (Superform Brochure) and reference books, cost models from similar processes (Thermoforming model and ATL model), were used to first extract data related to operation times, instead of being collected from the actual process that had not been implement yet. Because of being in its concept stage, it was difficult to gather information directly from the actual process or any other primary source.

According to the Pareto analysis of the Potential DC-TTMs against DS, the main DC-TTMs should fall under five of the six DC categories listed in Table 6.4.

Samples of the information on potential DC-TTMs found using the DS-DC TTMs Library are shown in Figures 6.14 to 6.16.

DC-TTM	Process Sources	Heuristic Sources	Paper-based & Internet Sources	Equipment Sources
Estimating Techniques (EsT)	✓	✓	✓	✓
Survey Research Techniques (SRT)	✓	✓	✓	✓
Team Working and Consensus (TWC) Techniques	✓	✓		
Work Design and Methods Engineering (WDME)				
Engineering Research and Management Practices (ERMP)	✓		✓	✓
Diagramming and Charting Techniques (DCT)			✓	

Table 6.4 Potential Data Collection Categories for the identified Data Sources for Double Diaphragm Forming Process - DDF Cost Model

Data Collection Techniques, Tools and Methods

Method: Comparative Estimating

References: Currie, R. M., Work Study, Pitman Publishing, ISBN 0273009591

Function: Work measurement technique in which the time for a job is evaluated by comparing the work in it with the work in a series of similar jobs (benchmarks), whose work content has been measured.

Inputs: It uses synthetic data supplemented by Time Study, MTM or any other appropriate work measurement technique. This data is the work content of a representative selection of jobs, used as benchmarks, and which have been arranged into broad bands of time. This arranging of jobs is referred to as 'slotting'. Other inputs are the estimator judgement of the appropriate time band (and therefore the work value applicable) to which a new job is assigned when comparing it against the benchmark jobs. And also complexity factors or ratios are used.

Outputs: It gives an acceptable answer for the total of work values (i.e. work content) of all the jobs a worker/operator (or a group of workers/operators) may do in a certain period of time.

Personnel: Engineers with manufacturing experience who have been trained to use this work measurement technique.

Equipment: Paper, comparative estimate forms/tables containing time bands for jobs (slots), pencil.

Environment: It may be used in any environment where work is undertaken, e g manufacturing, distribution, office, warehousing, etc

Sequence:

1. Get all details and information concerning the job to be measured.

2. After gathering all details of the job to be measured, the job is broken down into recognisable pieces called work elements, which cover the entire operation/activity.

3. The job under study (and/or its elements) is compared with the benchmark jobs contained in a table, and a judgement is made as to which band of jobs or slot (from the time interval chart) it most nearly compares with.

4. This arrangement of benchmark jobs into bands of time or slotting, depends on the nature of the application, which establishes the series of time intervals (of increasing magnitude) to be selected. The range of these time intervals should cover the complete range of jobs normally to be expected in the particular type of work under consideration.

5. The job under analysis is then judge to be of a particular band, and the appropriate average work value (in minutes) from the time interval table is taken as being the work value applicable.

Figure 6.14 Comparative Estimating (EsT Category)

Data Collection Techniques, Tools and Methods

Method: Flow Diagram

References: Currie, R. M., Work Study, Pitman Publishing, ISBN 0273009591

Function: It shows location of the various activities involved in an operation/process with respect to departments, working areas and their sequence. It is associated with a particular man, material or equipment FPC.

Inputs: Processes, operations, tasks and/or activities categorised as operation, transportation, inspection, delay, storage and/or hold. Inputs (area layout, distances, sequence and type of activities, etc) can be identified by visual observation or by judgement during design of a process.

Outputs: Diagram substantially to scale of the working area, illustrating the specific operations/activities (identified by their numbered symbols) of a process carried out and their sequence, and the routes followed by workers, materials or equipment in their execution. It can be used at different levels of detail, i.e., process level, process operation level, activity/task level.

Personnel: Engineers with manufacturing experience who have been trained to use the process flow technique.

Equipment: Paper, pencil

Environment: It may be used in any environment where work is undertaken, e. g., manufacturing, distribution, office, warehousing, etc.

Sequence:

1. Draw a scale layout of the area in which the subject(s) involved is (are) to move.

2. Indicate on the layout the areas where operations take place.

3. Use appropriate symbol to indicate the type of operation that is taking place, including a brief description of the operation or activity.

4. Draw lines from one operation area to another to indicate the sequence of operations involved.

5. The routes followed in transport are shown by joining the symbols in sequence by a line which represents as nearly as possible the paths of movement of the subject (worker, equipment, material) concerned.

6. The numbered transport symbols, which form part of the flow line, have to show direction of movement.

Figure 6.15 Flow Diagram (DCT Category)

Data Collection Techniques, Tools and Methods

Method: Networks, CPM and PERT

References: Joseph J. Moder, Cecil R. Phillips, Edward W. davis. Project management with CPM, PERT and precedence diagramming. Third Edition. ISBN 0-442-25415-6

Function: To record costs, times, and other forms of data within a network and node structure including probabilities and constraints. In such a manner, data is identified and categorised as well as rated.

Inputs: Times, costs, probabilities, subjective scoring

Outputs: Diagram illustrating the operations and their sequence which may include operation times. The method can be used at different levels of detail, i.e. process level, process operation level, activity/task level. Other outputs include ranked lists of data on an ordinal scale as well as ratings of listed time and cost constraints among others in order to sort and direct the data collection effort.

Personnel: Engineers with manufacturing experience who have been trained to use the CPM, PERT and network techniques. Proprietary software packages exist that are specifically designed for such an analysis, though spreadsheet based programs can also be constructed.

Equipment: Paper, pencil, Excel spreadsheet, and project management automated tools.

Environment: Project management techniques may be used in any environment where work is undertaken, e.g. manufacturing, distribution, or office environments.

Sequence:

1. Create a checklist of steps within the manufacturing process. This is the most important step allowing for planning and changes when the cost exercise is not yet fully committed by data collection.
2. The checklist may also be substituted for a graphical representation of the process in a nodal network format.
3. Utilise the objectives and constraints of the cost exercise and include within the network diagram or spreadsheet format of the PERT technique.
4. Elicit expert opinion on optimistic, pessimistic and most likely values for a quantity to be measured. This quantity maybe cost or time for example.
5. Use the PERT technique that is built on the Beta distribution to calculate a mean quantity as well as variance.
6. Enter a desired value for the quantity to be measured for each process step.
7. Assume the quantities are normally distributed and calculate probabilities that the desired values can be reached.

Figure 6.16 Network Analysis Tools (ERMP Category)

6.3.2.2 Case Study 3: Five axes CNC Machine Station

The process was almost fully automated, but it was considered that modelling the great diversity of components and machining processes could be an interesting challenge as from the point of view of identifying data sources and data collection tools. The development of a CER based on a milling process was being considered.

The machines at the machining station were commonly dedicated to the manufacture of specific component groups e.g. small ‘soft’ metal (aluminium) components, large ‘hard’ metal (steel, titanium) components, and small, soft metal components at high speed machining. CERs specific to such a machine/component group were the expected outcomes. Data for the three machining centres was held in Microsoft Access databases.

In this instance, the important point was the possibility of establishing a trade-off in terms of the data available and the data required to build the model and identifying the parameters in the process that add most to the cost resource to be estimated, based on the cost model characteristics identified by using the Model Scoping Framework.

6.3.2.3 Case Study 4: Rear Flange (O-rings) Manufacturing

In this case study, the main point was during the MSF exercise when participants were encouraged to discuss issues related to the model accuracy and the effects of design decisions on the characteristics and expected output of the model. The consequences of the assumptions, allowances and considerations that the cost model developer has to consider in order to accommodate for those design decisions were also brought up into the discussion.

The process was fully operative at production level. The MSF exercise uncovered several interesting points that concern the cost of the entire engine. The overall life cycle of the engine design had 6 stages. As expected, with each progressing stage, the accuracy of the cost increases. For instance, at stage 1 all that can be said about the ring concerns the material and its shape (circular shape). At this stage in the design the cost model accuracy is +/- 25%. Small changes (for example, a hole) in the design at Stage 2, may cause the costing accuracy to increase to +/- 15%. Stage 3 will include the major details, for instance, drilled holes will result in the accuracy of the estimate to be +/- 10%. The final design at stage 4 includes all the details and is the finished design with an accuracy of +/- 5%. The last two stages are the maintenance or spares cost and the cost of disposal.

The cost of the engine is broken down into percentages of the total cost for each of the sub-assemblies. Trade-offs between weight, cost and engine lifecycle are carried out and the costing of individual components is conducted to increase the accuracy of the cost estimate. Another use for the cost estimate using the above method is to drive innovation. A reasonable target cost is set and the designer has to aim as close to this one as possible. It is not expected that the target cost will be met but it should drive innovation towards this target.

6.4 Final Remarks

This Chapter consists of the results, analysis and discussion on the final stages of the research methodology, namely Evaluation and Validation. The above paragraphs describe the proposed Cost Modelling Methodology and the components added to it to improve the data collection stage which has been identified as one of the bottlenecks in the process of building cost models.

Cases studies have been conducted and discussed to validate both the CMD Methodology (Case Study 1) and the Model Scoping tool (Case Studies 2 to 4). The outcomes from the case studies contributed to refine the proposed new CMD Methodology, identify its limitations, and verify the suitability of its tools (Model Scoping Framework and Paired Comparison Matrix) for the development of cost models. The main conclusions and further work are discussed in Chapter 7.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

7.1 Background

The research investigation followed an Exploratory Sequential Multi-Method (ESMM) research design (Creswell and Plano Clark, 2007). The following sections describe the main conclusions derived from the investigation based on the outputs from the different stages of the research methodology; namely Exploration, Formulation, Evaluation and Validation.

The main contribution of this research investigation includes a new CMD Methodology to bring visibility, structure and improved accuracy to the generation of cost models.

The proposed CMD Methodology gives emphasis to the initial stages of the cost modelling process, i.e., data identification and collection of input data. An improvement tool, the Model Scoping Framework, was also developed and integrated as part of the new CMD Methodology as a instrument to identify relationships between potential cost data sources, cost model characteristics and data collection tools and techniques.

Additional contributions, no less important, include the creation of a Taxonomy and a Library for Data Sources, Data Collection TTMs, and Data types and the application of the Paired Comparison Matrix to identify and select input data types.

7.2 Conclusions

7.2.1 Proposed Cost Modelling Development Methodology

- The proposed CMD Methodology was validated up to the point of identifying the Data Collection TTMs which was one of the main objectives of the present research investigation. Further work is still required to test the Methodology to its full potential. This should include measuring the time taken to develop a cost model first time available (with and without the Methodology and compare results (measuring current time and the new time).
- Feedback from cost engineers and estimators on the Methodology described it as:
  a. Structured and coherent approach for developing cost models.
  b. Allowing incorporating the concept of model purpose definition in the early stage of the model development process.

c. Providing a common language and well defined stages.
d. Having the potential for shortening development times and for bringing cost models in line with the business objective they are developed for.

7.2.2 Applicability of the CMSF for the Development of Cost Models

- A Cost Model Scoping Framework (CMSF) was developed, reviewed and validated using manufacturing processes and products at different development stages (concept, prototype and commercial) and the expertise of Manufacturing and cost modelling and estimating staff.
- The processes ranged from automated CNC machining centres for the production of small hard metal aircraft components, Double Diaphragm Forming for the production of composite components, and O-rings components for turbine engines.
- The CMSF was successfully used to gather information related to the manufacturing process as well as information necessary to determine the cost model characteristics.
- The CMSF was developed to be used primarily for processes and products in the manufacturing industry, particularly Aerospace and the like. To make the CMSF universally applicable in other industries, new features such as new production processes and product types are required.
- The results from the Case Studies showed that:
  a. The CMSF helped to identify contradictions between model purpose and characteristics, and provides 'what if' analysis
  b. It mainly probed its suitability as a communication and consensus tool to define and identify customer requirements, model characteristics, resources, and data owners. Hence assisting in the planning process for the development of cost models
  c. It assisted in the creation of the initial data collection plan.
  d. It highlighted constraints and pointed out contradictions between cost model requirements and model characteristics before problems arose. The tool made participants (cost engineers and cost builders) reflect on their cost modelling practices and 'heuristics'.

- During the case studies, the CMSF brought to light issues that may be hidden until it is too late or expensive in the cost modelling process to put them right; for instance:
  a. *DDF Cost Model - Case Study 2:* gaps in the data and cost information required, alternative ways of generating cost information when there is none available as first hand data; lack of knowledge on the process as it was in its definition stage.
  b. *Five Axis CNC Machine Centre – Case Study 3:* establishing boundaries on the data available and the data required to build the model; identifying the parameters in the process that add most to the cost resource to be estimated.
  c. *Rear Flange (O-rings) Manufacturing – Case Study 4:* the Model Scoping exercise made participants to discuss issues concerning the accuracy of the model and the effect of the design decisions on the output of the model and the assumptions, allowances and considerations that the cost developer has to make in order to accommodate for those design decisions.

7.2.3 Identifying and selecting Input Data Types, DS and DC-TTMs

- Main types of data used to develop cost models (product and process features and process activities) and the primary sources of each data type were identified and classified.
- Focus group exercises were held to identify the strengths of individual relationships. From the results those relationships with the greatest strengths were used for the development of the Library of Data Sources, Data Collection TTMs and Data Types.
- A Library of data types for specific manufacturing processes was also created using the input from manufacturing processes at the participant organisations.
- A Taxonomy for Data Sources and Data Collection tools, methods and techniques was created. Thirty three Data Sources were identified along the different stages of the investigation including those collected from the surveys, literature review, and interviews.
- A total of 35 individual methods, tools and techniques for data identification and collection were also identified and sorted into six data

collection categories according to a set of generic features and individual characteristics. A comprehensive list of data types was also produced. This provided essential information for selecting between alternative tools and techniques.

- This library of DS, data types and DC-TTMs constitutes an important source document and provides guidance and a starting point for the data collection tasks for the development of a cost model.

7.2.3.1 Using the PC Matrix for Identifying and selecting Input Data Types

- Utilising a modified version of the PC method, the research investigation confirmed that all variables within cost models, fall into three data types; namely, product features, process features, and process activities.
- The focus group exercise, participants' feedback and the analysis of the gathered data made possible to gain a deeper understanding on the nature and basic structure of cost drivers and to corroborate the claim that they are the result of different combinations of product features, process features, and process activities and not as previously assumed made by individual features or activities.
- The relationship and attribute components of the PC tool did not assist as much as expected on the generation of the product features, process features and process activities database. Their contribution on the identification of product features, process features and process activities is still to be explored.

7.3 Recommendations for Further Work

- Investigating the application of the proposed Cost Model Development Methodology and the Cost Model Scoping Framework (CMDF) in industries other than manufacturing.
- Developing a performance system to evaluate the effectiveness of the methods incorporated into the Methodology for data identification and collection as well as developing indicators for measuring the performance of the CMSF.
- Use of alternative decision making/ranking tools other than Paired Comparison Analysis for the selection of the cost drivers and predictor

variables for the cost models (as identified from the literature review and validation of the CMSF) and compare the results from the use of these tools against other data analysis tools including regression analysis and analysis of variance.

- Further work is required to bring automation to the process and take away, at least to some extent, the task of manually identifying the DS and DC-TTMs from the hands of the experts. This would alleviate the risk associated with losing the 'know-how' of the data collection tasks in the CMDP.

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APPENDICES

APPENDIX A: QUESTIONNAIRE I

A1 Survey Questionnaire I – Sample

Name of cost model:	Sheet Metal Manufacturing	Model Code [redacted]
What are the functions of the cost model? Who uses the output from the model?	Rapid evaluation to determine the should cost of sheet metal fabrications (with the minimum of data input and minimum of user expertise). To conduct Cost reduction exercises (batch sizes, make the most of one profile) for Customer-Supplier negotiations. It is used to validate the use of new technology (i.e. Laser Cutting &CNC bending) to suppliers. To reduce the cost of components by 50% in 2 years (target). Manufacturing Engineers, Procurement, Designers Project Engineers and Managers. Even some suppliers in order to conduct costing review and adjustments	
	Name of manufacturing/commercial processes	Frequency/year
Name of manufacturing or commercial processes that can be costed using the model? How repetitive are these processes?	Laser Cutting, CNC Press break Bending of sheet metal components. Procurement and Negotiations with suppliers. The process is very accurate and repetitive. It is feels that only improved technology will change this. However this is not relevant to [redacted] by the time being as the model meets target and exceeds these requirements.	3000 parts/year [redacted] requires no more than a hundred plus parts at a time (parts=brackets)
	Data Inputs	Data Outputs
List data inputs and outputs & specify whether: subjective data (S) non-subjective (N) historical data (H) Note: specify names of data eg: for drilling these could be material type, feed rate for drill, drill revs/min	Non subjective: Cost of the material used and type of material (Laser Cutting) Distance to cut Operation costs Hourly rate (including adm. & quality costs) Laser cutting rate Cost per bend (CNC bending) Design data: no. of holes to drill, material thickness, anchor nut, welds, spacers, plunged hole, finishing. Historical Data: Original costs, current supplier costs, RR machining tables. Subjective: Assumptions in terms of defining the worst scenario regarding estimates of operation costs Such as bend, weld, chamfered hole, anchor nut, plunged hole, spacer and painting costs. These estimates are made using experienced personnel in the fields of machining operations. Suppliers are asked for maximum level (%) of cost reduction when making a particular part (6% in this case). This information is used as baseline to start the cost reduction exercise. E.g. rough estimate of perimeter to cut.	Cost per component or batch of component. By using a Cost Control Formula and a data base, it is possible to obtain: Cost of making a bracket, for instance.
What is the estimating accuracy of the model? Is this level of accuracy required & why?	The accuracy of the model is good enough to show a massive cost reduction when using Laser cutting, and comparing the outputs from the model against suppliers' cost reduction estimate. Any cost reduction below the baseline (suppliers' estimation, 6%) was good. Initially, the price of a bracket for [redacted] was £90. It was expected that by using Laser Cutting, the cost of a bracket fell down at £3 (96.7% cost reduction). The first drive was from £90 to £10, and then from £10 to £3. (90 points below suppliers expectation). The target was set at 50%, it was found to produce approx. 70% cost reduction, and at some cases even 90% cost reduction , based upon the final cost per component (unit cost). The batch size of the product does not justified "finite" the model too much (100 units) The estimated accuracy of the model is 50% as expected. Cutting time is accurate in 70%.	
What is the precision of the model?	The output from the model is an estimate. This is not a finite model	
	Person/Job	Expertise needed to use model
Who estimates costs using the model? What expertise do they need to use the model?	Suppliers Manufacturing Engineers, Procurement, Designers Project Engineers and Managers	Low level of expertise is required to operate the model. The interface is user friendly.

	Time & resources required to collect input data	Time & resources required to convert input data to cost data
Time & resources for preparing cost estimate using the model? Note: resources may include manpower, equipment such as computers	Component Drawings and features Material costs (steel, titanium, stain steel) Machining process expertise Supplier information in terms of cost of the product (tooling and operation costs) Machine specifications.	Computers, excel spreadsheets (database), Cost control formula. The time is almost instantaneous.
Time & resources for developing the cost model? Note: resources may include manpower, equipment such as computers	The model was developed in three months of manpower (1/4 man/year). Resources: computers, spreadsheet Excel software, historical data from [redacted] machining tables, machinist expertise.	
What characteristics do you feel are important for cost models? E.g. accuracy, responsiveness	Consistency of response Accuracy	
How do you select processes for which to develop cost models?	[redacted] is required to cut costs by 50% in the next two years. For this purpose, a market review is conducted and processes are examined in order to make cost saving measures and apply a fair price policy. For the process of Laser Cutting, a market review was conducted in the motor industry.	
Did you initially review the process and if so how did you:	Yes	
Identify process review data to be collected	Analysing the process and manufacturing operations involved as well as all activities involved in making the product. Drawings Experience	
Collect that data	Manually. Conducting a market research of various suppliers, searching for best machining methods for sheet metal cutting.	
Review the process	Market review: application of the technology (laser), type of machine, running and servicing problems, extra equipment, etc	
Decide the characteristics of the cost model to be developed?	By establishing what is required as output, manufacturing process involved, batch size required, level of cost saving	
How did you identify the process 'cost driving' activities?	By analysing the process activities and the operation costs. (cutting speed, use of the profile shape, comparison between current and newest technology, etc)	
How did you decide what data needed to be collected to establish CERs for these 'cost driving' activities?	Analysing results from the market review. Establishing the activities that add the higher costs to the process and/or represent the higher savings.	
How did you collect this data?	Manually	
How did you structure & store this data in order that the CER can be established?	Database (spreadsheet)	
How did you establish the CER, i.e. cost model?	Using experience	
How do you test the validity of the cost model?	Comparison against suppliers' estimates of level of cost reduction.(Baseline)	
How do you test the estimating accuracy of the cost model?	Comparison against suppliers' estimates of level of cost reduction (Baseline). Comparison against the best current market price from suppliers involved.	
How frequently do you test the: Accuracy of cost model Precision of cost model Validity of cost model	 N/A N/A The model is validated when it is used in negotiations, against the best price available in the market	
How do you apply the cost models within business?		

Do any problems arise when... Gathering information? Using raw data to obtain cost information? Making use of cost information?	None.
Final Notes	Historically Rolls Royce has been associated with the ideal of quality produced products. This heritage has been upheld in the past with parts being purchased based on performance of component, weight of component, quality of component and ability of supplier to deliver. Cost has always been the last consideration to Rolls Royce, with overpricing or poor negotiating due to the lack of a cost model to determine fair price. Today, however, this has changed in order to cope with the more competitive, improved and continuously changing environment of manufacturing. Nowadays: Components are designed for optimum manufacture (air-fix type parts from one piece of sheet) Utilising the latest technology in machining. Suppliers are involved from very early at the design stage of a product. All operations are costed. All tooling is costed. Target costs are estimated then set. Component is designed to target cost. Component is bought as near to target cost as possible. Further model improvement: More comprehensive study of surface treatment processes

A2 Survey Questionnaire I – Cost Models involved in the Survey

Tables A2.1, A2.2, and A2.3 list the models, including areas of applications and a brief description. An extracted sample consisting of a brief summary of the information collected by Questionnaire I for models from each of the different organisations involved are described in Tables A2.4, A2.5, A2.6, A2.7 and A2.8.

Company Code	Cost Model Code	Business Area	Description of use
A	RR1	Engineering	Used in the bid process & Design to Cost
	RR2	Procurement	Analysis of historical data for competitive benchmarking (using Statistical software)
	RR3	Advance Propulsion System Design	Used in the Design Optimisation Process
	RR4	Turbine Systems	Design optimisation (component level) developed by [redacted] & [redacted].
	RR5	Turbine Systems	Identification of the commercial viability of capability acquisition programmes (component level)
	RR6	Commercial defence (Europe)	Life Cycle Costing. Material & Labour Costs of in service engines. Probability simulation of operating costs.
	RR7	Procurement	Rapid evaluation of small to medium size components machined from bars, using advance-turning centres.
	RR8	Procurement	Rapid evaluation of to determine the should cost of sheet metal fabrications.
B	DAF1	Procedure to cover the control of a/c BIDS & Programmes	This programme ensures all dept. check key cost drivers when making a Bid and do not work on it without approval.
	DAF2		Due to the worldwide nature of market, different products made, lead-time variations & level of data given to Bid. Many products are created using experience.
	DAF3	Project Control & Monitoring	Allows for all aspects of project release, control & monitoring
	DAF4	Configuration Lists	Configuration Lists build up a Database of actual past costs and project spends.
	DAF5	Customer Enquiry & Quotation Proc.	Check list & quotation procedure, for engineering costs.
	DAF6	Project Variation	Identified how project changes are administrated
C	BAM1	Design Option / Trade Studies	Process time & material cost estimation, including part location onto assembly, fastener installation, application of sealants, etc.
	BAM2		Process time & material cost estimation for carbon fibre composite panels incorporating Honeycomb cores
	BAM3		Process time & material cost estimation for CFC panels without Honeycomb cores
	BAM4		Process time & material cost estimation for CFC spars & ribs (internal structures)
	BAM5		Process time & material cost estimation for super plastic formed & diffusion bonded components
	BAM6		Process time & material cost estimation for metallic sheet components (small to medium)
	BAM7	Design Option / Trade Studies	Process time & material cost estimation for stretch-formed skins (medium-large)
	BAM8		Based on analysis of a cost database, covers several processes including SPF, DB, Welding. Gives good indications as to the cost, without the need of all the information, with estimates justifiable against similar parts within the database ("actuals")
	BAM9		Process time & material cost estimation for aluminium machined parts (milling)

Table A2.1 Cost Models discussed using Questionnaire I (Companies A, B, C)

Company Code	Cost Model Code	Business Area	Description of use
D	BAA1	Composite Wing Programme	Estimate the time required to produce a component using automated Tape Laying
	BAA2		Estimate the cost of a component manufactured using the Resin Transfer Moulding Process
	BAA3		Estimate the time required to manufacture a component using Hard Tape Laying
	BAA4		To simulate a factory used to manufacture all the major wing box components, estimate manufacturing time, throughput, quantity of tooling required, etc.
	BAA5		To simulate a factory used to assemble all the major wing box components, estimate manufacturing time, throughput, quantity of tooling required, etc.
	BAA6		Describes the manufacturing process for the components of a "black metal" composite wing box, and generate a breakdown of the manufacturing times/costs
	BAA7		Estimate the time required to assemble a rib to a spar using integral spar stiffeners (metal or composite rib)
	BAA8		Estimate the time required to assemble a metal/composite skin to ribs.
	BAA9		Estimate the time required to assemble a metal/composite skin panel to the spars.
	BAA10		Estimate the time required to transport a clamped/unclamped skin panel to the final assembly jig.
	BAA11		Estimate the time required to clean and apply interlay sealant to a wing skin panel/wing box structure.
	BAA12		Estimate the time required to assemble pylon fittings to a wing box structure/wing skin panel.
	BAA13	Future Projects Office/A3XX project	Assessing the most cost effective Aircraft configuration, either as a whole (complete aircraft structure) as part as an optimisation cycle or for slightly more detailed studies.
	BAA14	(R&T) Research & Technology	Assessing impact of Advanced manufacturing methods on Hybrid Laminar Flow Wing
	BAA15	Research & Technology	Generating cost rates (cost per hole/cost per hour, etc.). For Laser Drilling.
	BAA16		Cost impact. Automation & conventional assembly for Aircraft structures (typically leading edges)
	BAA17		As above, except for it looks at the complete assembly of a wing (stage/jig)
	BAA18	Research & Technology	Determines process time to route & press components. Variables include materials, part size & features, number off, optimum batch size.
	BAA19		Determines the hourly charge rate for equipment for use in ABC. Variables include m/c utilisation, labour rate, floor area, cost of equipment, facilities costs, rate of return, economic life. Uses DCF & NPV
	BAA20	R&T Future Projects	Determines direct operating costs for single aisle & long range [redacted] aircraft ([redacted]). Commercially sensitive.
	BAA21	Research & Technology	Takes data from FE (Finite Element) model and determine manufacturing & materials cost for wing skins & stringers. Used in the cost assessment of new alloys.
	BAA22		Calculates manufacturing & materials cost based on geometry of wing skin stringers. Models available in ICAD and spreadsheet

Table A2.2 Cost Models discussed using Questionnaire I (Company D-Part 1)

Company Code	Cost Model Code	Business Area	Description of use
D	BAA23	R&T Commercial Estimating.	Determines materials & manufacturing cost of metallic ribs.
	BAA24		Determines materials & manufacturing cost of metallic spars.
	BAA25		Determines materials & manufacturing cost of metallic stringers.
	BAA26	Research & Technology	Determines materials & manufacturing cost of friction stir welding aircraft-components.
	BAA27		Determines materials & manufacturing cost using conventional assembly processes and Laser welding and jig welding
	BAA28		Determines manufacturing-process time to machine metallic ribs. Used when a high level of detail is known.
	BAA29	Research & Technology [redacted] (AI)	Determines DMC using line & shop maintenance costs, fuel burn, delay & cancellation costs & spares holding costs. Commercially sensitive.
	BAA30		Determine cost implement modifications. Commercially sensitive.
	BAA31	Research & Technology	Determines manufacturing time-process. Exists on paper only but not difficult to put into spreadsheet.
	BAA32	Commercial Estimating	Generating whole aircraft programme recurring costs & associated breakdowns
	BAA33		Generating whole aircraft programme non-recurring costs & associated breakdowns
	BAA34		Business Cost Simulation
	BAA35		Generating Learning Curve DMA
	BAA36		Generating estimates for detail part manufacture: Forming Machining Composite Lay-up Drilling, etc
	BAA37		Generating estimates for Raw material and fasteners: Forgings Extrusions Plate, etc
	BAA38	Commercial Estimating/ Composite Wing Programme	Generating Estimates for CFRP Manufacturing Processes (including Factory Simulation)
E	HYD1	Estimating, Production, Management	Used to produce a man hour rate for the production of NC turned components. A verification tool for negotiations between [redacted] and [redacted]. Aim to be 75% accuracy of actual. Ball Park figure.

Table A2.3 Cost Models discussed using Questionnaire I (Company D-Part 2 and Company E)

Cost Model Code	On the Cost Model	On the Model User/ Developer	On Data Identification and Collection	On the Cost Model Development Process
RR1	Used to prepare a Bid from full definition concept design parameters of engine. Paves way for the physical design or product realisation; Full Concept Definition; Actual costs-benchmark for predictive; Calibrate Inputs: Labour Hours Labour Cost Material Type Number to produce Learning curve Intangible complexity factor calibrate to industry standards Outputs: Full cost break-down Assembly by material/labour Sub-assembly by material/labour Individual parts by material/labour Total cost It maps the effect of the learning curve on the time Accuracy: Within +/-5%.	Used by Cost Engineer and Cost estimator, supporting design stage of product. Marketing use the output for a Bid Need a level of expertise and knowledge of software.	It can be hours up to a few weeks. Operational data and systems are a problem. Cost is down to specifications accessibility and the right people all acting in the right way.	Difficulties of using cost information when it is used without knowledge of risks involved. It could be used with no knowing the impact that a poor estimate could have. Size of project is important with the bigger the project, the larger the cost impact, the larger the risk so confidence is required. Understanding homogeneity to benchmark is another issue, using quite detailed information. Data availability e.g. needs for large input. Design of aircraft engine is volatile. Units can be an issue i.e. SI units and Imperial. Problem disappearing now that $ is take as standard. DoD methodology approved.

Table A2.4 Brief outline description of Model RR1 (Company A) according to main areas covered by Questionnaire I and Interview

Cost Model Code	On the Cost Model	On the Model User/ Developer	On Data Identification and Collection	On the Cost Model Development Process
DAF1 to DAF6	Production in small batch sizes. Four main product areas: Screen-Printing: Advertising, Posters, Placards, Business cards etc. Vacuum Forming: Specialists parts, JIT boxes etc. Woodwork Shop: Cases, Shop interior Aerospace Interiors: Aircraft seating, Interior walls, Spares Cost modelling and estimating is used to prepare a Bid. Each of the above business areas are very individual, with different products being manufactured on a project basis, and each job being individually costed (because of the small batch size and high product variability). The information of a job is not stored on a database, and two similar jobs are costed using experience rather than software based cost estimations. Inputs: Labour Hours Labour Rates Material Type and product type Number to produce Outputs: Total cost Main cost drivers: labour and material costs.	Need a high level of product and processes expertise and knowledge of the business.	It can be hours up to a few weeks. High product variability means that no two jobs are the same. Maybe a family structure should be created to allow estimation using similar parts. Since there is no record of previous work carried out, the input on a CNC machine, for example, has to be repeated for identical jobs, as a consequence of the absence of capability which allow storing the input data.	Difficulties of using cost information. At the moment this work is carried out using absorption costing methods or marginal costing. Pressure from OEMs on acquiring a Management Information System and a customised cost database, This task requires ten years of historical data being examined for this purpose. Because of the business nature and financial constraints, No MRP system has been implemented. There is not a cost estimation software solution either.

Table A2.5 Brief outline description of Models DAF1 to DAF6 (Company B) according to main areas covered by Questionnaire I and Interview

Cost Model Code	On the Cost Model	On the Model User/ Developer	On Data Identification and Collection	On the Cost Model Development Process
BAM1 to BAM9	The primary aim is to enable trade-off between design and cost. They provide information on the optimum design solution for Designers and Production Engineers. For Capacity and Resources Planning, they provide information regarding Manufacturing Capabilities (in man-hours). Also they support pricing, cost management, and value engineering. Also used for MOD/DOD audit trail in initial Bid. Inputs: Models Drivers: Process Knowledge, number of operations, product and project characteristics. Product Drivers: Geometric, Physical, Material, Different specifications Outputs: depend on tool used. Include: Designers case; Man hours per operation; Materials cost £; Man hours set-up cost £; Cost can be broken down in much more detail. E.g. sub process break-down. Outputs can also be single costs. The main aim is to see areas of cost. Charge rate is derived from the association of man/hours to cost (done at the actual rate). Accuracy: Within +/- 15% in terms of man/hours compared to industrial engineering times. Historical data is used to compare against and to calibrate accuracy to target. The level of accuracy is set by the cost engineering department and was chosen as a simplification baseline.	The Technical Directory, Cost Engineering, Design, Advance Technology, Production, R&T, Commercial Department. There is a multi-departmental usage of the model, i.e. integrated teams composed of people (with cost expertise, designers) from several departments use the outputs at different stages of the project and extent. However just the Cost Engineering Group creates the model and estimates the cost. There are only 10 users. It is expected to be used by designers in future.	Data Collection Time varies according to the process. Data collection is performed manually from separate departments. Review of process involved is conducted for understanding the process at a good level of detail. Tools used: flow diagrams, process planning, process flow, process experts' interviews. Machining tables required. Boundaries have to be introduced (max length, etc). Time & resources required to convert input data to cost data vary from drawing to drawing (computer labour intensive process). For instance, individual ply (layer) areas perimeter required (e.g. panel) take up to 1/2 day. For simple design inputs, this time is down to 5 min. E.g. length, width, breadth, depth.	Sufficient help is embedded to allow use without specialist knowledge. Basic to none manufacturing knowledge, design experience, or computer skills. Takes 3/6 man/months to develop the model. The model is based in Windows Excel spreadsheet The Cost Engineer is responsible for collating the data, with support of Procurement. Up to 80% of the modelling time is used to collect information from several sources at different locations involving tedious work. Automatic data collection required ideally using Catia. Nowadays, the process rely on paper based information, timing information is computer based. No opportunity of retrieval

Table A2.6 Brief outline description of Models BAM1 to BAM9 (Company C) according to main areas covered by Questionnaire I and Interview

Cost Model Code	On the Cost Model	On the Model User/ Developer	On Data Identification and Collection	On the Cost Model Development Process
BAA16 BAA17	Used to prepare estimates to assess the viability of robotics for automation of wing manufacture for the Automated handling, fastening and drilling of components associated with Wing Box Assembly. Inputs: Subjective at the moment of interview. Input data dependent on the process experts (Robotics, R&T). By the end of the project is it expected all the data inputs will become non-subjective data. This is ongoing as project matures. Outputs: Cost comparison between current technology and future developments. Graph comparison of NPV against change in cost (over ten years), as every wing produced has to be cost effective. Accuracy: Unknown at this stage. Expected within +/-5%, allowing comparison with existing technologies.	Cost Engineering estimates using the model. Expert knowledge is required. Aim is to produce model that is usable elsewhere. Going to take 4 months to develop the models.	Information from robotics specialists and companies concerning their speed and capability. While from internal sources information on drilling and handling collected. 500 man-hours required to collect input data. 1000 man hours to convert input data to cost data. No choice for process review data, only data that is available. Opinions from Commercial Estimating, Finance, Cost Control and relevant suppliers (vendors). Cost control will use sequel to target cost the process above and below efficiency.	One month into project at the moment of interview. Process is new, concept created by [redacted]. Task is to verify if process possible and is viable. Model has to be able to indicate to Project what will impact on cost and what modifications can be done. Improving the capability can be trade-off between the savings in man-hours and the capital cost (NPV against Delta Cost). Precision is required for internal security. If a large cost to implement, the impact on [redacted] could be significant

Table A2.7 Brief outline description of Models BAA16 and BAA17 (Company D) according to main areas covered by Questionnaire I and Interview

Cost Model Code	On the Cost Model	On the Model User/ Developer	On Data Identification and Collection	On the Cost Model Development Process
HYD1	The model is used to produce a man hour rate for the production of NC turned components (NC Tooling, 3 axis, 5 axis machining). Very repetitive when processes are set for many units of production. However, one off production is the common case they are used for. For one off production experience determines the modelling and estimating method. It is used only as a negotiating and sales tool for [redacted] with [redacted]. Method used to develop the model consist of the application of Process Mapping. Inputs: Shopfloor data from [redacted] and [redacted] are used to create the core of the model. Drawing details. Material type, tool size, speeds/feeds, stock removal, cutter size, complexity of shape. Length, Breadth, Width and Depth of cut. The input from the drawing is very subjective with experience, gained from previous jobs. Outputs: Breakdown of tooling process with the man-hours required for each individual step. These man-hours can be converted to cost. Accuracy: 25% is the aimed accuracy of the model. Traditional techniques are estimated to be 10%. The model can reach up to 15% accuracy at the moment of interview.	[redacted] uses it for negotiation purposes. Essentially for verification of price on components. Outputs are used by Estimating team, Production and Management Sales, Customer. Essentially from the shop floor up. This is a verification tool for negotiations between [redacted] and [redacted]. Ball Park figure. Good understanding of engineering drawings, with engineering knowledge of machine capability. Verification knowledge is also required for complex jobs.	Concurrent engineering identify the process 'cost driving' activities. And [redacted] decide what data needed to be collected to establish CERs. [redacted] identifies the cost drivers from their experience of the process and cost estimating, using historical data, machine information and engineering drawings. Insufficient information requires the estimate to be from the front end. By reviewing the drawing, and using the engineer expertise and experience, the cost driving activities express themselves. Work is carried out on a tool type, with data collection conducted by [redacted] and [redacted]. The model is then developed and can only be changed by agreement, unless there is a change in specification.	It takes half an hour to a week for one man to prepare cost estimates using the model. This model is used only for one customer, and it is unknown the production quantity involved. Parameters to be interpreted from drawings. Specialised machining skills required for interpretation and analysis of data. This is an ongoing process, making it an evolutionary model. The data is component based with standard tables for feeds and speeds. Drawings can change in design or specifications and need to be verified every time this happens. The validity of the outputs is checked against actual costs, and against manual quote.

Table A2.8 Brief outline description of Model HYD1 (Company E) according to main areas covered by Questionnaire I and Interview.

A3 Survey Questionnaire I – Causes for Concern associated with the CMDP

Issues for concern as identified by the survey and associated with the model development process (highlighted in red on the Cause-Root Diagram of Figure 5.3) include:

- Changes in drawings, design or specifications need to be verified. The process can be repeated for every job. Very repetitive when the processes are set for many units of production.
- Some of the models are very sensitive. Sensitivity depends on the number of drivers of the model. The more the accuracy required, more sensitive the model will be, and more drivers will be required. Therefore, sensitivity analysis is required to reduce the number of inputs.
- Up to 80% of the modelling time is used to collect information from several sources (papers, computing systems, drawings, manuals), sometimes at different locations and involving tedious work. Automatic data collection is required. For some models, the process mainly relies on paper based information; however, timing information is, most often than not, computer based. There may be no opportunity of retrieval.
- In some cases, there is not enough time to understand the process; instead, a 'piecemeal' examination of the process is conducted. Procurement data requirement can be a long process.
- It is expected that current technological advances and IT solutions will change this, reducing hundreds of different systems to a few integrated ones. Ideally, quality data gathered electronically could be an advantage, and it could help to perform statistical analysis and to refine the necessary data.
- Suppliers are quite prepared to 'show off' their manufacturing processes, but restrictive on divulging financial information. Also, it is difficult to get real time and reliable data. Data has to be up to date or there will be no confidence on the validation and accuracy.
- It is necessary to know the location of the companies and the correct personnel, to get the right level of detail of the data and to ask the right questions.
- Estimators have to be aware of the scaling factor to be used, since some data does not follow a linear proportion (such as weight and

speed). Also, new technology is more of a debate because of the risk involved in utilising such technology. It is important to understand the application of technology in a wider way and forecast improvements; hence, reducing the level of uncertainty.

- The quality of the estimate is driven by the quality of the information gathered. Sometimes data has no definable quality. Problems arise trying to get production and manufacturing people to understand what data is required to make the estimate and identify cost drivers. According to one of the interviewees this is because “engineering people are not cost people by nature”.
- Also people, who do not have the necessary background and make use of the information, can misunderstand it. Sometimes, the information has been collected inappropriately or used incorrectly, which can create the wrong scenario for a process that is commercially sensitive.
- There is a lack of consistency in terms of the information available, which depend very much on the approach followed, namely, Accountancy or Cost Engineering.
- There is a need for visibility. Even though the model should be developed to be user friendly and compatible, a “Superuser” will sometimes be required in order to deal with all the hidden part or layer of the model, which is beyond the interface (codes, data to update, etc.)
- Operational data, systems and design “volatility” of some products (aircraft engine design is volatile, for instance) could be a problem as costing is down to specifications accessibility and the right people all acting in the right way as a team.
- There are some problems to agree the currency conversion to be used, in order to maintain consistency. Units can also be an issue i.e. SI units and Imperial. Problems are fading as some organisations are using US dollar (US $) as standard currency.
- Difficulties of using cost information when it is used without knowledge of risks involved. It could be used with absolute faith without knowing the impact that a poor estimate could have. Size of project is also important; with the bigger the project, the larger the cost impact, and the larger the risk. So high level of confidence is required.

- Some models are over ten years old (even 15 years old). If the model's assumptions are out-dated, the validity of the input data is compromised and so are the outputs of the model. Therefore, data management and control procedures for follow up or feedback should be in place to ensure the model's predicting capability are up to date and enhanced. The feedback should be the follow up or comparison of the costs actually incurred against the costs originally estimated by the model.
- Lot of variability within suppliers factories due to layout, overheads, machine types, configurations, work plans, batch sizes, among other factors
- Internal barriers hinder the collecting of data. It is extremely difficult to obtain data from shop floor, due to working practices, employees' sensitivity (disagreement) and difficulties with the workers' union as Time & Motion Studies are still perceived negatively by the workforce. And also they (i.e. the unions and workers) do not respond well to interference.
- Cost information is always controversial with people always challenging the estimate. The cost estimate is only as good as the assumptions made during development. 30% rely on core experience and confidentiality, 70% are 'overlooked'.
- The disclosure of information from manufacturing centres is sometimes difficult. 'Never' provided in the correct format or exactly what is required.
- Information coming from suppliers is commercial sensitive. Therefore, this can cause difficulties when sharing information. Due to the commercially sensitive nature of the information there may be constraints on disclosing and publishing the final cost. This may be a potential problem when agreeing with the customer the format of the output costs.
- Solution turnaround time is driven by the computer hardware capabilities (server and computer speeds). The cost model turnaround time can be considerably slow even when the changes on the product design are small. Therefore, the model is as good as the equipment it is used on.
- Despite having enough information on different projects, it is necessary to ensure the applicability of data to the project under consideration by

using individuals' subjective judgement and experience. It is difficult to establish if the data that comes from previous negotiations from past programmes, is suitable enough.

- For instance, the price may be £1/kg for material but subject to the purchase of 5000kg to have this price. Is the data suitable for the final application?
- When there is no data available, industry best practice or standards (on data material) are applied. Even then, is it reasonable to make those assumptions? Are they suitable to the project or not?
- The company usually only has data on the final product (for instance, wing assembly) while the rest of the information comes from industrial partners and external sources. All these data and even data from previous negotiations have to be considered subjective. Expert judgement and experience is needed.
- There are bottlenecks at different stages. For some processes such as the assembly process, for instance, there may be plenty of data available to link aircraft component costs to specific assembly operations. For others, such as the manufacturing processes, however, it is necessary to start from scratch (bottleneck).

APPENDIX B: QUESTIONNAIRE II

B1 Survey Questionnaire II – Template

Cost Modelling Questionnaire

As part of a PhD research in the area of Cost Modelling, I am conducting an investigation examining the Cost Model Development Process in terms of the relationships between model purpose and model characteristics.

In addition, I am looking into the data sources, and data collection tools and techniques used by cost engineers and estimators when developing cost models/estimates and how the appropriate selection of these elements can contribute to make cost model generation faster, easier and more structured.

To this end, I have prepared a survey to gain an understanding of the factors that need considering when developing cost models/estimates and on the variety of data sources and data collection tools available to the cost engineer/estimator.

I would be very grateful if you could complete the survey and send your response by **22 December 2007**. Most of the questions are multiple choice, so it should take just a few minutes to complete. A summary report containing the main findings of the research will be sent to you on completion of the investigation.

The information provided by you will be kept **absolutely confidential** and will be **used for research purposes only**.

Thank you very much in advance for your time and support.

If you have questions concerning this questionnaire, please contact me at ydelgado@dmu.ac.uk or phone Professor D J Stockton on +44 (0) 116 2577074

1. Industry in which your company is primarily active. (Please tick as appropriate)

- Aerospace
- Electronics
- Construction
- Software
- Other - Please Specify

2. What activities does your company undertake? (Please tick all that apply)

- Design & manufacture of complete products/OEM (e.g. automobiles, aircrafts)
- Design & manufacture of parts/sub-systems/sub-assemblies (e.g. brakes, avionics systems)
- Product Design only
- Product Manufacture only
- Design of parts/sub-systems/sub-assemblies

3. If applicable, which of the following Volumes of Production best describes your company? (Please tick as appropriate)

- One-off
- Low Volume
- High Volume

4. Which of the following Production Processes best describes your company? (Please tick as appropriate)

- Project
- Job Shop
- Batch Production
- Continuous Flow Line

5. In your organisation, which of the following do you estimate? (Please tick all that apply)

- Process Costs
- Product Costs
- Process Times

6. What type of cost models/estimates do you usually generate? (Please tick all that apply)

- Conceptual Estimates/Order of Magnitude
- Preliminary Estimates
- Prototype/Detailed Estimates
- Other - please specify

7. In your company, which of the following business units is primarily responsible for the development of cost models (i.e. cost engineering function)? (Please tick as appropriate)

- Design
- Manufacturing
- Procurement
- Other - please specify

8. In your company, which of the following business units is primarily responsible for preparing the cost estimates (i.e. cost estimating function)? (Please tick as appropriate)

- Design
- Manufacturing
- Procurement
- Other - please specify

9. On average, for the staff who make a cost estimate/model, how many man-hours per week would they spend generating cost estimates or cost models? (Please select as appropriate)

- Less than 5 hours per week
- Between 5 and 10 hours per week
- Between 10 and 20 hours per week
- Between 20 and 30 hours per week
- 30 or more hours per week

10. On average, how many cost engineers/estimators are actively engaged in estimating? (Please select as appropriate)

- One estimator
- Between 2 and 10 estimators
- Between 10 and 20 estimators
- Between 20 and 30 estimators
- 30 or more estimators

11. Which of the following resources do you normally estimate? (Please tick all that apply)

- Material
- Direct Labour
- Indirect Labour
- Process Time
- Capital Asset (i.e. equipment, machinery)
- Manning Levels
- Other - please specify

12. Based on your experience, what is the maximum number of variables you would use in your model/estimate?

Max No of Variables

13. Which of the following types of variables are normally used with in your models/estimates? (Please tick all that apply)

- Product Features (e.g. complete airframe, engine, L/D radio, material, no.of holes)
- Process Features (e.g. turning speed, no. of axes, feed speed, tool locator for an CNC machine centre)
- Process Activities (e.g. loading piece, machining, set up, inspection, boring operation, turning operation)
- Other - please specify

14. How do you *normally* obtain your costs/times? (Please tick all that apply)

- Carry out detailed cost estimates
- Generate Cost Model
- Other - please specify

15. If applicable, which of the following software tools do you most frequently use to create cost models? (Please tick all that apply)

- Spreadsheets (e.g. Excel, Lotus etc)
- Price H/S
- Cost Advantage
- Enterprise Cost Management
- SEER™ Suite of Tools
- Free Parametric Models (e.g. from NASA, etc)
- Advanced Computing tools (e.g. AI, Expert Systems/Knowledge based tools)
- Simulation/Virtual Reality Tools (e.g. SIMUL8, WITNESS, Techmatics)
- Other - please specify

16. What type of models do you develop? (Please tick all that apply)

- Statistical Models (e.g. Regression Analysis, Time Series and Causal Cost Models)
- Knowledge Based Models
- Risk Analysis (Monte Carlo Simulation)
- Other - please specify

17. What methods do you currently use to collect data?

18. What data sources do you use?

19. Based on your experience, how important (in a scale of 1 to 4) are the factors listed below when generating the type of estimates/models you produce? (Please select as appropriate)

(a) Cost Estimate/Model Purpose (i.e. what is it to be used for?)

- (1) Not Important
- (2) Important to some extent
- (3) Important
- (4) Very Important

(b) Availability of Cost Data

- (1) Not Important
- (2) Important to some extent
- (3) Important
- (4) Very Important

(c) Time available to collect data

- (1) Not Important
- (2) Important to some extent
- (3) Important
- (4) Very Important

(d) Time available to input data

- (1) Not Important
- (2) Important to some extent
- (3) Important
- (4) Very Important

(e) Time available to generate the model/estimate

- (1) Not Important
- (2) Important to some extent
- (3) Important
- (4) Very Important

(f) Data Collection tools and techniques available

- (1) Not Important
- (2) Important to some extent
- (3) Important
- (4) Very Important

(g) Estimating Accuracy

- (1) Not Important
- (2) Important to some extent
- (3) Important
- (4) Very Important

(h) Estimator expertise/skills

- (1) Not Important
- (2) Important to some extent
- (3) Important
- (4) Very Important

(i) Level of detail/ type of estimate (i.e., detailed estimate, order of magnitude)

- (1) Not Important
- (2) Important to some extent
- (3) Important
- (4) Very Important

20. How time consuming are the following steps for developing cost models? (Please select as appropriate)

(a) Select product/process to be costed

- Hours - Days - Weeks - Months - Years

(b) Identify product/process data to be collected

- Hours - Days - Weeks - Months - Years

(c) Define cost model characteristics

- Hours - Days - Weeks - Months - Years

(d) Identify Data Sources

- Hours - Days - Weeks - Months - Years

(e) Identify Data Collection Methods/Tools

- Hours - Days - Weeks - Months - Years

(f) Collect process/product data

- Hours - Days - Weeks - Months - Years

(g) Identify Cost Drivers

- Hours - Days - Weeks - Months - Years

(h) Identify data needed to build the cost model and collect data

- Hours - Days - Weeks - Months - Years

(i) Structure and analyse data to define the cost model/estimate

- Hours - Days - Weeks - Months - Years

(j) Test validity and estimating accuracy of the cost model/estimate

- Hours - Days - Weeks - Months - Years

(k) Apply models within the business

- Hours - Days - Weeks - Months - Years

21. What features would you like to see that aids your cost modelling process?

22. What is the end use for the models/estimates you create or use? (Please tick all that apply)

- Cost Reduction
- Process Time Reduction
- Process Evaluation
- Process Improvement
- Process Development
- Product Evaluation
- Product Improvement
- Product Development
- Standard Data Generation
- Capacity Planning
- Production Scheduling
- Pricing and/or Quotations
- Business Planning
- Investment Planning
- Procurement Decisions
- Manufacturing Decisions
- Process Comparison
- Bid Analysis
- Cost Weight Trade Off
- Target Costing
- Should Cost
- Life Cycle Costing
- Make or Buy
- Outsourcing
- Other - please specify

23. If applicable, what decision levels do you develop cost models/estimates for? (Please tick all that apply)

- Strategic Level
- Tactical Level
- Operational Level

24. Is the inclusion of risk analysis important within your costing/estimating process? (Please select as appropriate)

- Yes
- No
- Does not apply

Company Information (Optional)

25. How many employees does your company have?

Company Name:

Company Address:

Summary Report - Mailing Details

26. Contact details for sending the summary report. (Please preferibly provide an email address)

Name (including title):

Email Address:

Fax Number:

Thank you for your time and co-operation.
The summary report will be sent out accordingly.

Submit

B2 Survey Questionnaire II – Company Profiling

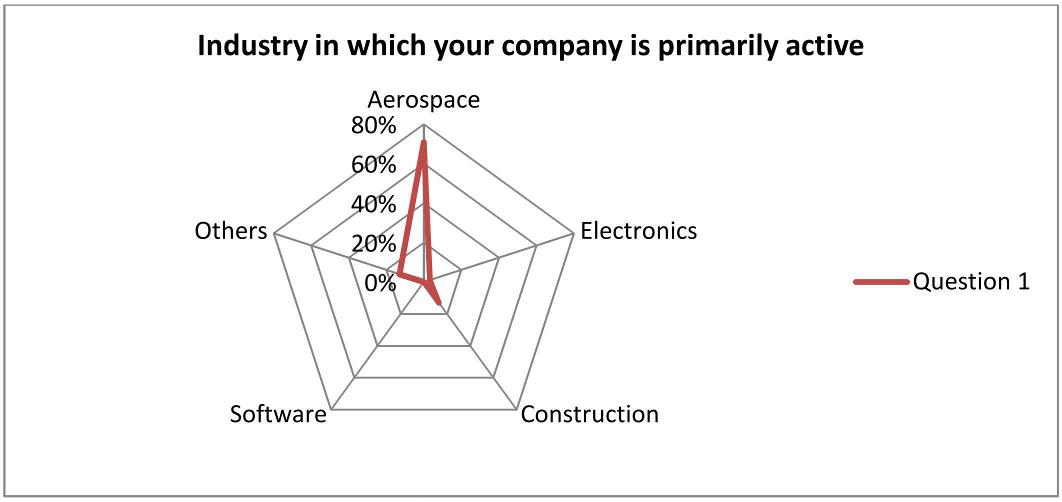

Figure B2.1 Industry sectors where the companies where primarily active

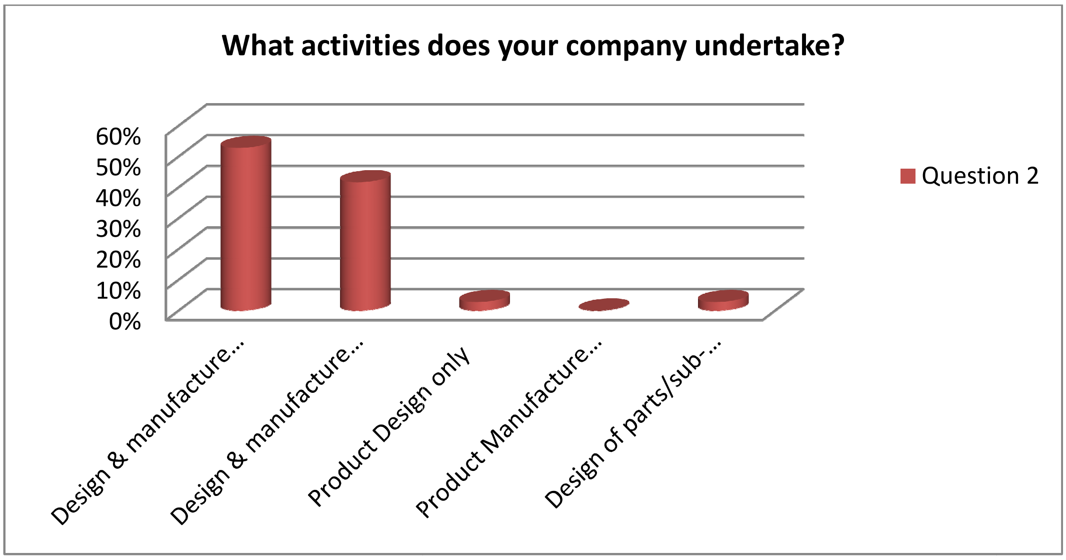

Figure B2.2 Industry sectors where the companies where primarily active

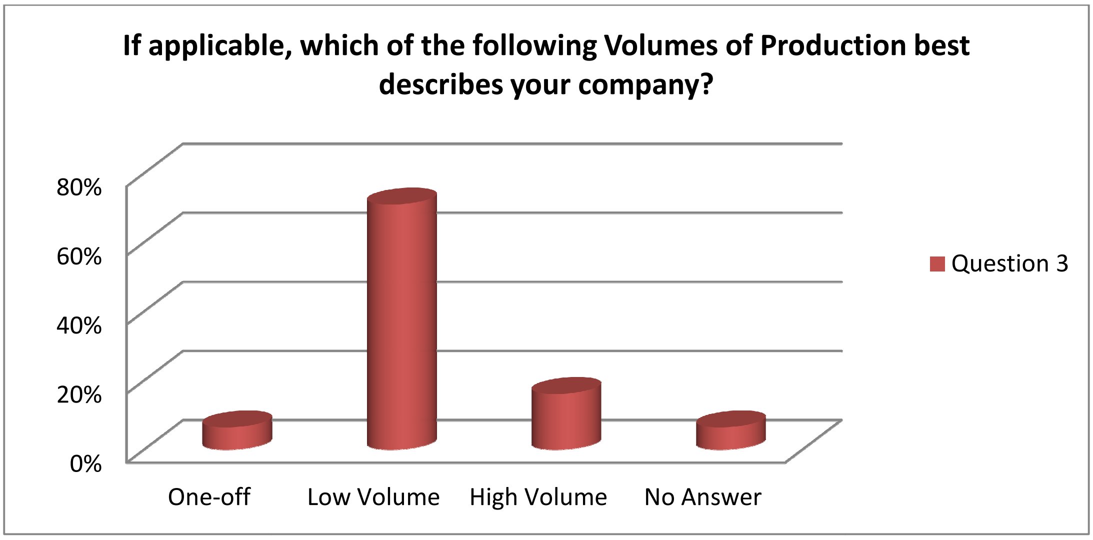

Figure B2.3 Company classification according to Production Volumes

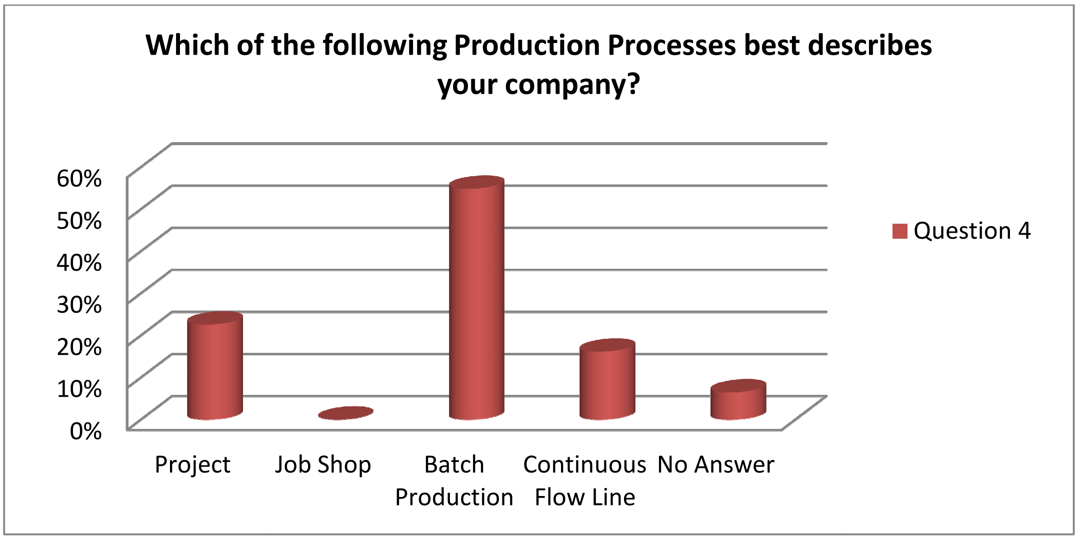

Figure B2.4 Company classification according to Production Processes

B3: Survey Questionnaire II - Cost Engineering and Estimating Functions

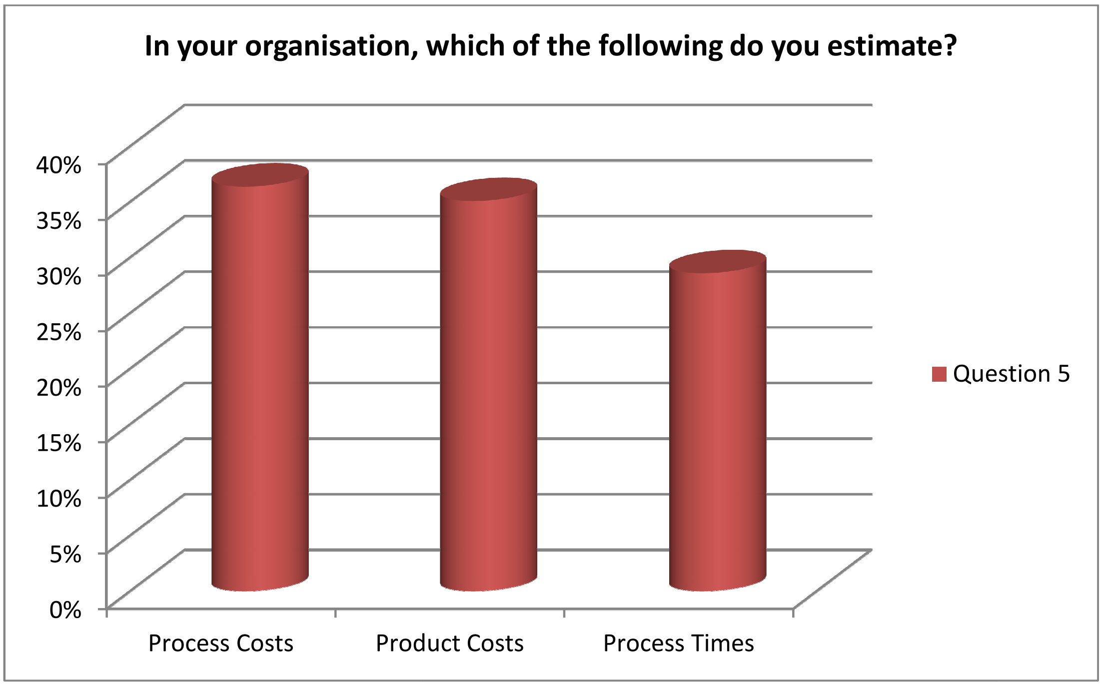

Figure B3.1: Major cost resources cost models and estimates are prepared for.

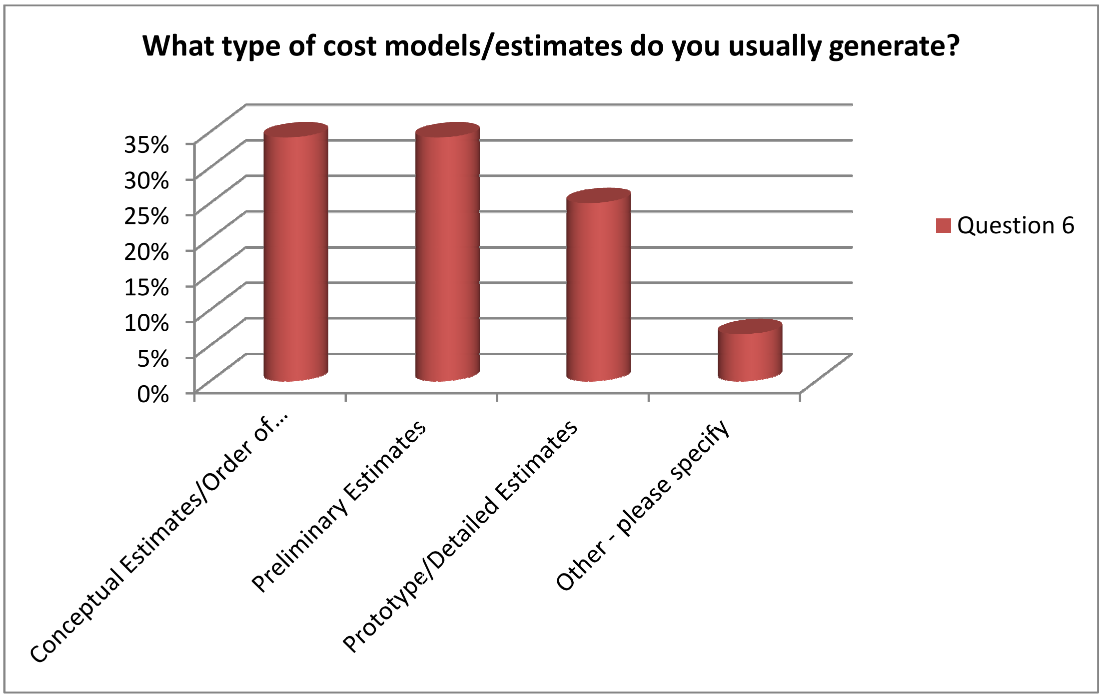

Figure B3.2: Types of cost models and estimates usually generated.

Figure B3.3 Business Unit primarily responsible for the development of cost models

Figure B3.4 Business Unit primarily responsible for the preparation of the cost estimate

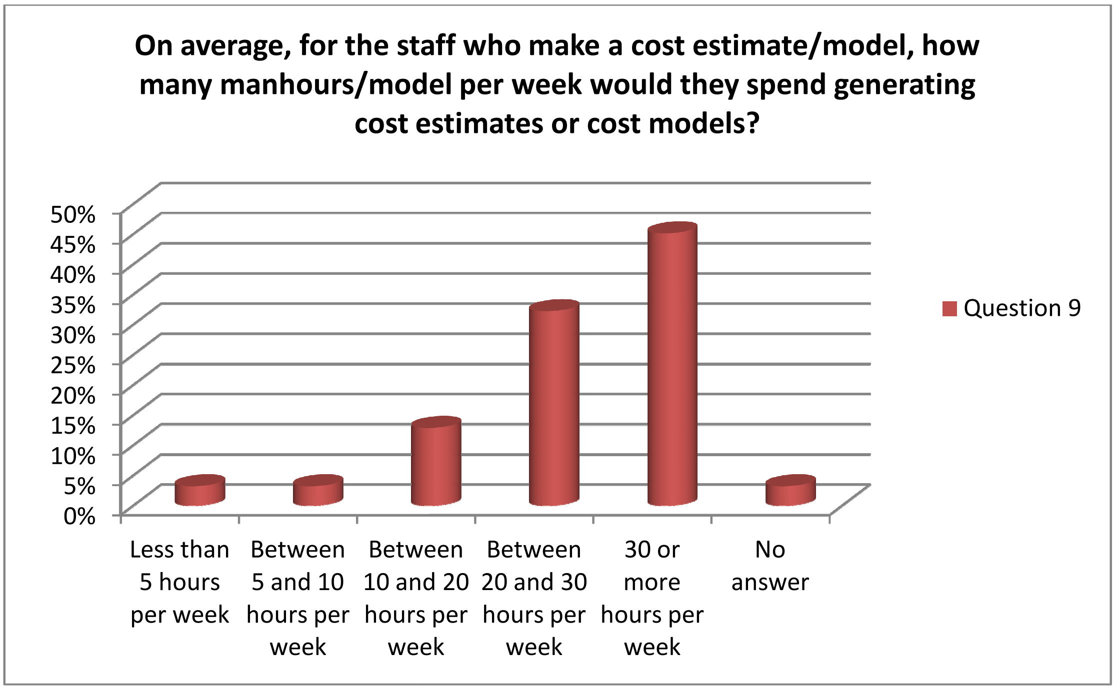

Figure B3.5 Manhours/model per week spent generating cost models and estimates

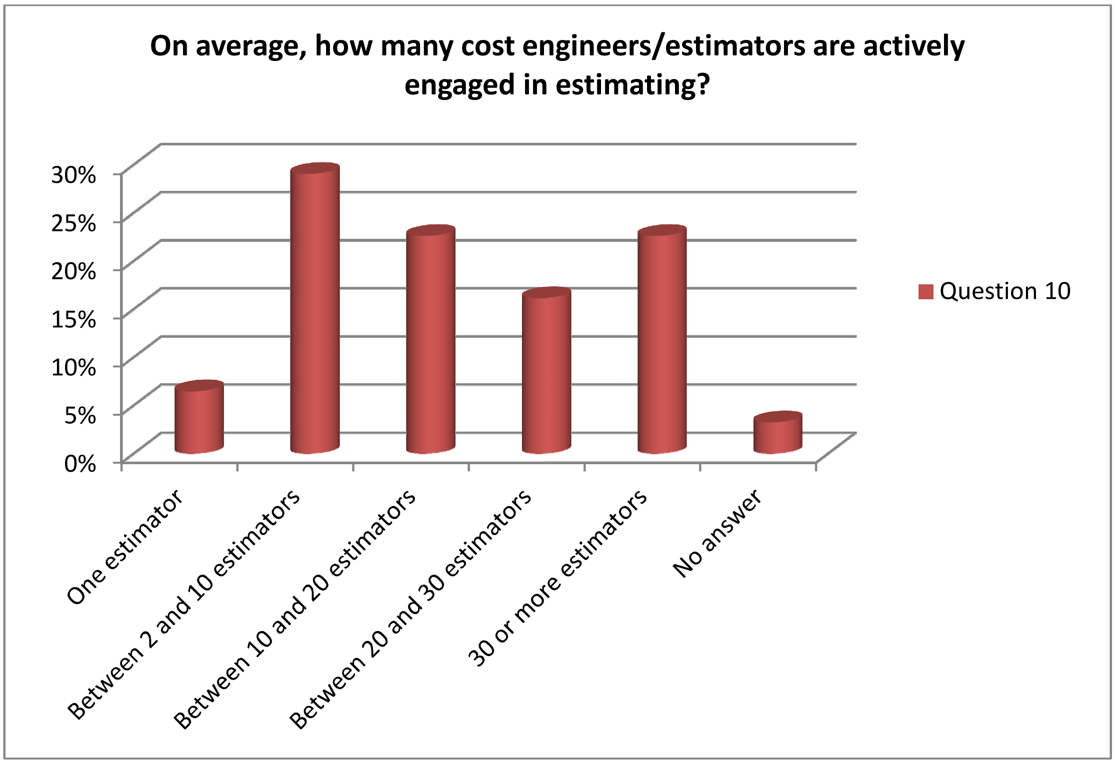

Figure B3.6 Cost engineers/estimators actively involved in estimating

APPENDIX C: MATRICES

C1 Data Source-Data Type Matrix – Template and Resources

Identify Potential Data Sources

	Resources to be costed						
Process Elements and Levels / **Product Features**	Direct Material	Indirect Material	Direct Labour	Indirect Labour	Process Time	Tooling	Manning Levels
Level 1 Product level							
Concept							
Preliminary design							
Prototype							
Commercial							
Level 2 Component level							
Concept							
Preliminary design							
Prototype							
Commercial							
Level 3 Component feature level							
Concept							
Preliminary design							
Prototype							
Commercial							
Process Features							
Level 1 Machine level							
Concept							
Preliminary design							
Prototype							
Commercial							
Level 2 Machine assembly level							
Concept							
Preliminary design							
Prototype							
Commercial							
Level 3 Sub-assembly level							
Concept							
Preliminary design							
Prototype							
Commercial							
Process Activities							
Level 1 Process level							
Concept							
Preliminary design							
Prototype							
Commercial							
Level 2 Process operation level							
Concept							
Preliminary design							
Prototype							
Commercial							
Level 3 Operational activity level							
Concept							
Preliminary design							
Prototype							
Commercial							

Figure C1.1 Data Source – Data Type (DC-Dtype) Matrix

C2 Data Source-Data Collection Tools Matrix – Template and Resources

Data Sources - Data Collection Tools Matrix

	Data Sources	1 - Process Sources							2 - Synthetic Sources		3 - Product Sources						4 - Equipment Sources					5 - Model Based Sources			6 - Paper/internet Sources							7 - Heuristic Sources		
	Data Collection Tools	1.1 Actual Process	1.2 Video of Process	1.3 Process Expert	1.4 Similar Processes	1.5 Visual and Control Tools (i)	1.6 Computerised Planning Systems (ERP, MRPI, MRPII, MPS)	1.7 Process controllers & automatic condition monitoring (ii)	2.1 Synthetic Standards (Standard Data)	2.2 PMTS Systems (MTM, MOST, MSD, MST)	3.1 Costed Components	3.2 CNC Programmes	3.3 CAD Files	3.4 Product Specification	3.5 Bill of Materials (BOM)	3.6 Engineering Drawings	4.1 Equipment Specification	4.2 Maintenance Manuals	4.3 Operating Manuals	4.4 Training Manuals	4.5 Equipment performance records	5.1 Process Models (iii)	5.2 Empirical Laws	5.3 Physical Models	6.1 Literature reviews	6.2 Departmental records (iv)	6.3 Operator's Black Book	6.4 Quality manuals/reports	6.5 Shopfloor Documentation, Planning & Control Sheets	6.6 Patents	6.7 World Wide Web (WWW)	7.1 Rules of Thumb	7.2 Personal Judgment/Common sense/Logic	7.3 Expert experience/opinion
A	Diagraming & Charting Techniques																																	
A1	2D & 3D Diagrams																																	
A2	Flow diagram																																	
A3	Flow process chart (m/c,matl,men)																																	
A4	IDEF process chart																																	
A5	Multiple activity chart																																	
A6	Outline process chart																																	
A7	Simultaneous motion cycle chart																																	
A8	String diagram																																	
A9	Travel chart																																	
A10	Two-handed process chart																																	
A11	Mind Mapping																																	
A12	Tree Diagram																																	
B	Motion & Time Study Techniques																																	
B1	Activity/Work Sampling																																	
B2	Checklist																																	
B3	Chronocyclegraphs																																	
B4	Cyclegraphs																																	
B5	Direct observation (matl,m/c,person,etc)																																	
B6	Video tape recording/Film analysis sheet																																	
B7	Stopwatch Time Study																																	
B8	Routing Sheet																																	
C	Estimating Techniques																																	
C1	Analytical estimating																																	
C2	Category estimating																																	
C3	Comparative estimating																																	
C4	Judgemental analysis technique (1)																																	

Figure C2.1 Data Source – Data Collection TTMs Matrix – Part I

B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ
	Data Sources - Data Collection Tools Matrix	1 - Process Sources	Actual Process	Video of Process	Process Expert	Similar Processes	Visual and Control Tools (i)	Computerised Planning Systems (ERP, MRPI, MRPII, MPS)	Process controllers & automatic condition monitoring (ii)	2 - Synthetic Sources	Synthetic Standards (Standard Data)	PMTS Systems (MTM, MOST, MSD, MST)	3 - Product Sources	Costed Components	CNC Programmes	CAD Files	Product Specification	Bill of Materials (BOM)	Engineering Drawings	4 - Equipment Sources	Equipment Specification	Maintenance Manuals	Operating Manuals	Training Manuals	Equipment performance records	5 - Model Based Sources	Process Models (iii)	Empirical Laws	Physical Models	6 - Paper/Internet Sources	Literature reviews	Departmental records (iv)	Operator's Black Book	Quality manuals/reports	Shopfloor Documentation, Planning & Control Sheets	Patents	World Wide Web (WWW)	7 - Heuristic Sources	Rules of Thumb	Personal Judgment/Common sense/Logic	Expert experience/opinion
	Data Sources		1.1	1.2	1.3	1.4	1.5	1.6	1.7		2.1	2.2		3.1	3.2	3.3	3.4	3.5	3.6		4.1	4.2	4.3	4.4	4.5		5.1	5.2	5.3		6.1	6.2	6.3	6.4	6.5	6.6	6.7		7.1	7.2	7.3
	Data Collection Tools																																								
B	Motion & Time Study Techniques																																								
B1	Activity/Work Sampling																																								
B2	Checklist																																								
B3	Chronocyclegraphs																																								
B4	Cyclegraphs																																								
B5	Direct observation (matl,m/c,person,etc)																																								
B6	Video tape recording/Film analysis sheet																																								
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B8	Routing Sheet																																								
C	Estimating Techniques																																								
C1	Analytical estimating																																								
C2	Category estimating																																								
C3	Comparative estimating																																								
C4	Judgemental analysis technique (1)																																								
D	Team Working Techniques																																								
D1	Brainstorming (2)																																								
D2	Creative thought																																								
D3	Decision modelling																																								
E	Survey Techniques																																								
E1	Interview																																								
E2	Questionnaires																																								
F	Engineering Practices																																								
F1	Experimentation (operational experiments)																																								
F2	Network analysis																																								
F3	Program Evaluation & Review Technique (PERT)																																								
F4	Critical Path Method (CPM)																																								
F5	Value Stream Mapping																																								

Figure C2.2 Data Source – Data Collection TTMs Matrix – Part II

C3 Paired Comparison for Wing Box Fabrication – Worked Example

The following paragraphs describe an example of the Paired Comparison Matrix applied to one of the processes selected, namely the Process of Wing Box Fabrication, as a worked example seemed more appropriate to describe the method. The same procedure was applied to other similar processes. The basic steps involved in identifying Product and Process Features and Process Activities are described below:

i. The session started with a facilitator (author) setting the "Problem Statement" or objectives of the exercise.

ii. The participants brainstormed to generate a short list of not more than 10 items per process element according to the type of cost resource to be estimated, the list was then numbered in no particular order. The information required was data on product features, such as photos of components of a certain range, engineering drawings or finished components. For process features the manufacturing process could be videoed, photographed or consisted of a typical sequence of tasks observed. Process activities could also be identified by direct observation or by a video of the process.

iii. The information also came from appropriate literature, such as books, technical reports, journals, maintenance and operating manuals. The familiarisation with the process and the range of products manufactured should occur before the PC exercise is conducted. Each identification task took approximately 10 minutes but it could be allowed to continue if good ideas were still flowing.

iv. The initial information and ideas generated during the session, i.e. identification of product features, process features and process activities, were collected by the facilitator on pre-designed templates or on a flip chart.

v. The spread sheet version of the PC procedure consisted of 6 worksheets. The first one was to fill in the information about the process and product under consideration, type of cost resource, dependant and predictor elements, and their levels (Figure C3.1).

Details of Process Elements and Levels

Product/Component	Wing Box		
Process	Wing Box Fabrication		
Type of Cost Resource	Recurring Process Time		
Dependant Element and Level	Product Feature	Level 1	Product Level
1st Predictor Element and Level	Process Activity	Level 1	Process Level
2nd Predictor Element and Level	Process Feature	Level 1	Machine Level

Figure C3.1 Worksheet 1 - Details of Process Elements and Levels

vi. The second worksheet of the form corresponded to the dependant element (Figure C3.2). Here the participants had to list the dependant cost elements (activities or features) that affect the cost resource the most (cost drivers).

Paired Comparison Table I: Dependant Element

Product/Component	Wing Box
Process	Wing Box Fabrication
Type of Cost Resource	Recurring Process Time
Dependant Element and Level of Detail	Product Feature Level 1 Product Level

No	Dependant Element Items	Vote Matrix							Totals
1	Top Skin	1 x	x 3	x 4	x 5	x 6	x 7	x 8	7
2	Bottom Skin	x 3	x 4	x 5	x 6	x 7	x 8		8
3	Front Spar	3 x	3 x	3 x	3 x	x 8			2
4	Rear Spar	4 x	4 x	4 x	x 8				3
5	Top Stringer	5 x	5 x	x 8					4
6	Bottom Stringer	6 x	x 8						5
7	Ribs	x 8							6
8	Manholes								1

Figure C3.2 Worksheet 2 – Dependant Cost Element for the Wing Box Fabrication Process

vii. The same procedure applied for the predictor elements on worksheets three and four, where the paired comparisons are made for Predictors 1 and 2 (Figure C3.3 and Figure C3.4). This could be done for the 3 different levels (level 1, 2 and 3). Each of the features where compared against each other by selecting the most appropriate (based on their effect on the resource being costed) and marking the most important with a vote.

viii. The idea behind the technique was that each item in the list was compared with every other one in pairs. It forced a decision between one of two options. In this case, the criterion for comparison was the cost resource type to be estimated, and the key decision was which element had the greatest effect on the cost resource.

Paired Comparison Table II: 1st Predictor Element

Product/Component	Wing Box
Process	Wing Box Fabrication
Type of Cost Resource	Recurring Process Time
1st Predictor Element and Level of Detail	Process Activity Level 1 Process Level

No	1st Predictor Items	Vote Matrix						Totals
1	Routing	1 x	1 x	x 4	x 5	1 x	x x	4
2	Drilling	2 x	x 4	x 5	2 x	x x		5
3	Assembly	x 4	x 5	3 x	x 7			6
4	Treatment	4 x	4 x	4 x				1
5	Inspection	5 x	5 x					2
6	Machining	x 7						7
7	SPF							5

Figure C3.3 Worksheet 3 – 1st Predictor Cost Element for the Wing Box Fabrication Process

2nd Predictor Resource Paired Comparison

Product/Component	Wing Box
Process	Wing Box Fabrication
Resource Measure Type Variable	Recurring Process Time
2nd Predictor Resource and Level of Detail	Process Feature Level 1 Machine Level

No	Process Activity	Vote Matrix			Totals
1	Machining Cell	x 2	x 3	x 4	4
2	Fabricating Cell	2 x	2 x		1
3	Treatment Cell	x 4			3
4	Assembly Cell				2

Figure C3.4 Worksheet 4 – 2nd Predictor Cost Element for the Wing Box Fabrication Process

ix. To complete the grid, the participants had to start always on Row 1, column 1. This has two numbers in the box 1 and 2. This instructs the person to compare item 1 with item 2. The item which had the greatest effect on the cost resource being considered was then circled or marked. Still on row 1, this action had to be repeated in column 2, this time items 1 and 3 were compared. The procedure was applied until row 1 is completed.

x. Moving to row 2, the comparison was made now starting with items 2 and 3, as the comparison between 1 and 2 was done in row 1. The same procedure continued until all rows were completed. Once the comparisons for each instance were done, the total was calculated on the right.

xi. The scores were totalled up to be evaluated and analysed.

xii. From the results of the paired comparison worksheets 2, 3 and 4 the relationship between the features and activities could be made (worksheet 5) (Figure C3.5). This time the comparisons were made between the different elements, i.e. each item of the predictor elements against each item of the dependant element. When a relation was identified between items of a predictor element and a dependant element, the scores for those particular items were multiplied. From the relationship matrix, the highest ranked dependant element (cost driver) can now have its attributes identified.

xiii. Finally the attributes of the activities and features were identified (worksheet 6) (Figure C3.6). Attributes are the measurable characteristics of the product/process feature or process activity that represent a cost driver. The step of transforming the general form of the relationships between process activities, product and process features and cost resources to their numerical form – known as Cost Estimating Relationships (CERs) - was not part of the scope of this project and can easily be a subject for another investigation.

For building the database of product and process features and process activities, the information gathered from the worksheets 2, 3 and 4 was used. Path Analysis was utilised for the analysis and result representation. The Relationship and Attribute components of the PC tool did not assist as much as expected with the generation of the library. Actually their contribution on the identification of the Process and Product Features and the Process activities is still to be explored. However, they were used to confirm the relationship among the activities and features when using the Path Analysis tool.

Resource Measure Type Variable: Recurring Process Time

Dependant Resource Type and Level: Product Feature Level 1 Product Level

	No	Totals of PC's		Top Skin	Bottom Skin	Front Spar	Rear Spar	Top Stringer	Bottom Stringer	Ribs	Manholes		
				Dependant Resource - Product Feature									
			No	1	2	3	4	5	6	7	8	9	10
			Totals of Comparisons	7	8	2	3	4	5	6	1	1	1
1st Predictor Resource / Process Activity / Level 1 Process Level	1	4	Routing					4	4		4		
	2	6	Drilling	6	6	6	6	6	6	6	6		
	3	7	Assembly	7	7	7	7	7	7	7	7		
	4	1	Treatment	1	1	1	1	1	1	1	1		
	5	2	Inspection	2	2	2	2	2	2	2	2		
	6	7	Machining	7	7	7	7			7			
	7	5	SPF							5	5		
	8												
	9												
	10												
2nd Predictor Resource / Process Feature / Level 1 Machine Level	1	4	Machining Cell	4	4	4	4			4			
	2	1	Fabricating Cell					1	1		1		
	3	3	Treatment Cell	3	3	3	3	3	3	3			
	4	2	Assembly Cell	2	2	2	2	2	2	2			
	5												
	6												
	7												
	8												
	9												
	10												
	Product of Paired Comparisons			98784	1E+05	28224	42336	8064	10080	423360	1680		
	Ranking			3	2	5	4	7	6	1	8		

Figure C3.5 Worksheet 5 – Relationships among Elements for the Wing Box Fabrication Process

Establishing Attributes of the Features and Activities

Resource Measure Type Variable

Product Feature Level 1 Product Level

		Links	Attributes
Product Feature Level 1 Product Level	RIBS		Lenght, Weight, Material
Process Activity Level 1 Process Level	Assembly		Manning levels, number of componets, size
	Machining		material, dimensions, feeds, speeds
	Drilling		material, dimensions, feeds, speeds, number of hole
	SPF		area of bonding, thickness, material
Process Feature Level 1 Machine Level	Machining		material, dimensions, feeds, speeds
	Assembly		jigs, rigs, fixtures, dimensions
	Treatment		location, size of component, tolerances

Figure C3.6 Worksheet 6 – Attributes for the Ribs (main cost driver) for the Wing Box Fabrication Process

C4 Data Source-Data Type Matrix – Analysis of Results

C4.1 Direct Material Cost

Process Activities

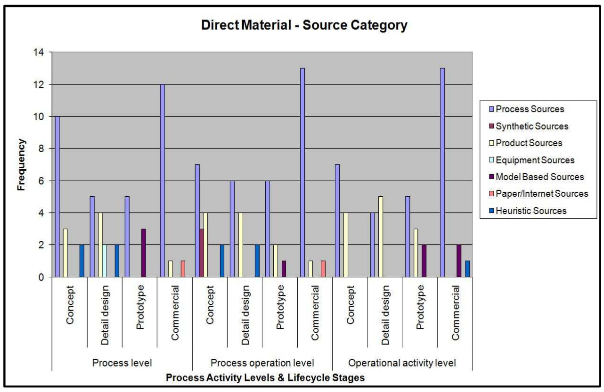

Figure C4.1 Data Sources of Process Activities for Direct Material

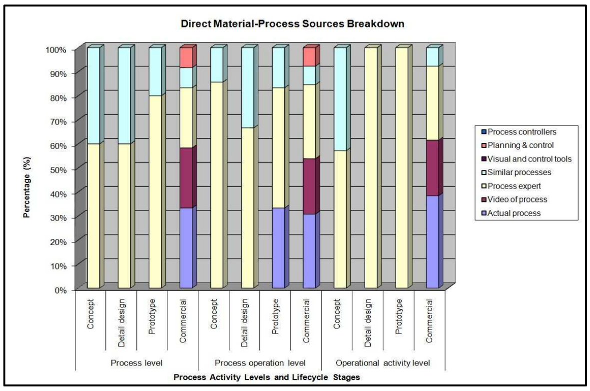

Figure C4.2 Process Sources Breakdown for Process Activities - Direct Material

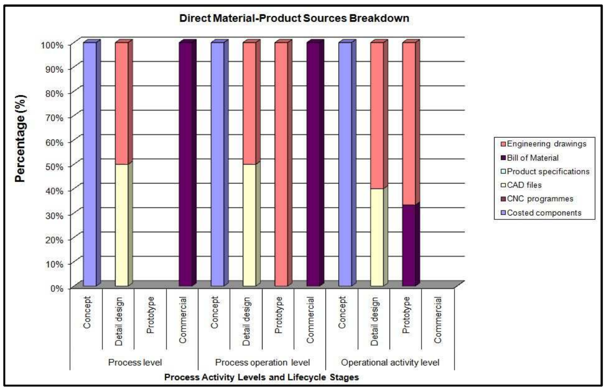

Figure C4.3 Product Sources Breakdown for Process Activities - Direct Material

Process Features

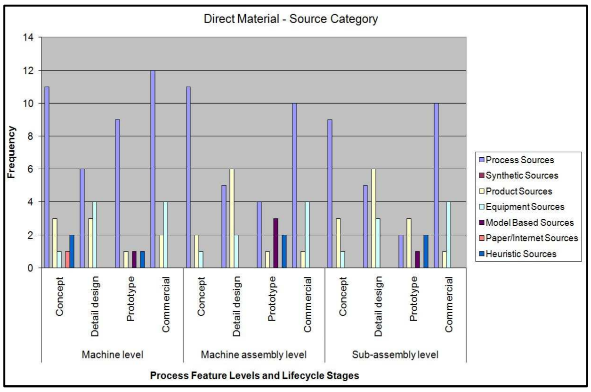

Figure C4.4 Data Sources of Process Features for Direct Material

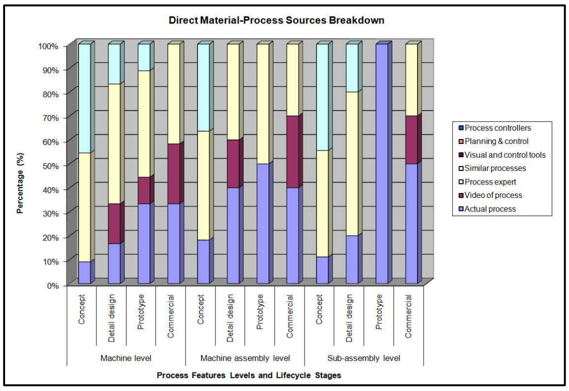

Figure C4.5 Data Process Sources Breakdown for Process Features - Direct Material

Product Features

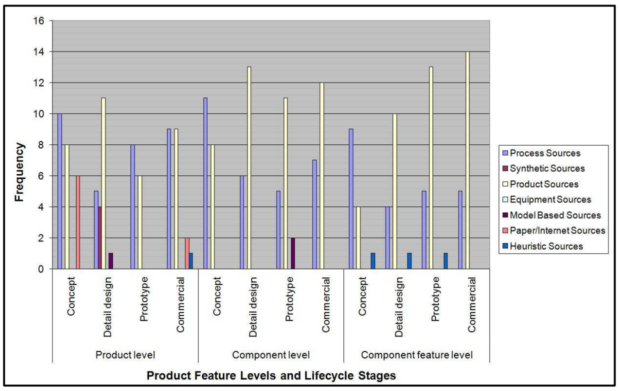

Figure C4.6 Data Sources of Product Features for Direct Material

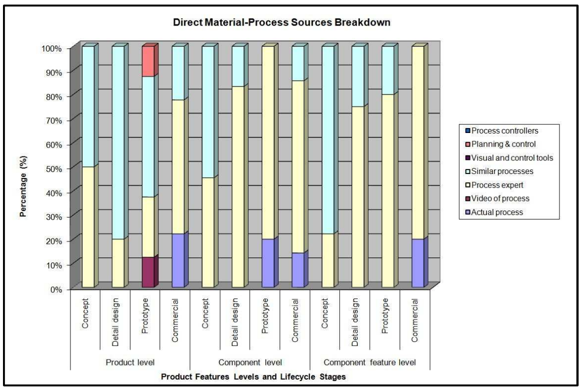

Figure C4.7 Data Process Sources Breakdown for Product Features - Direct Material

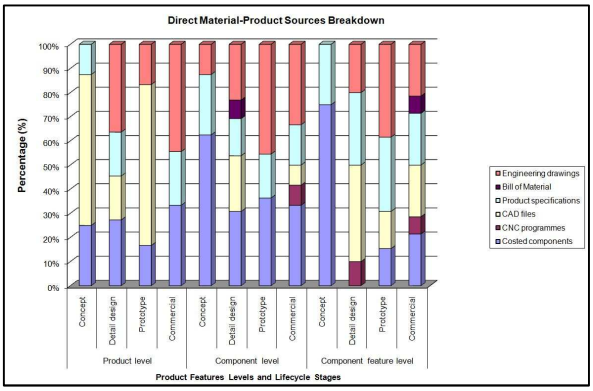

Figure C4.8 Data Product Sources Breakdown for Product Features - Direct Material

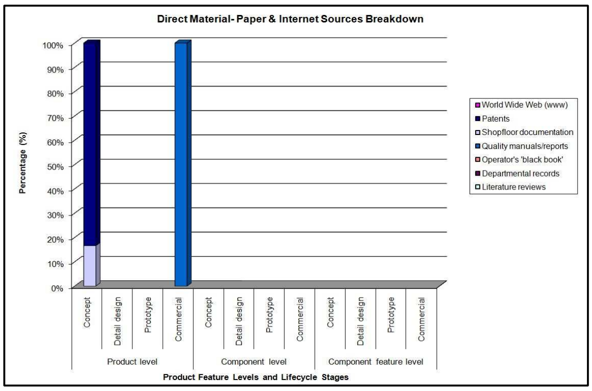

Figure C4.9 Paper and Internet Sources Breakdown for Product Features - Direct Material

C4.2 Direct Labour Cost

Process Activities

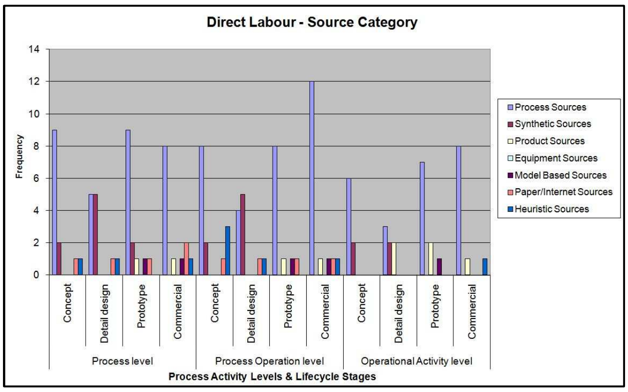

Figure C4.10 Data Sources of Process Activity information for Direct Labour

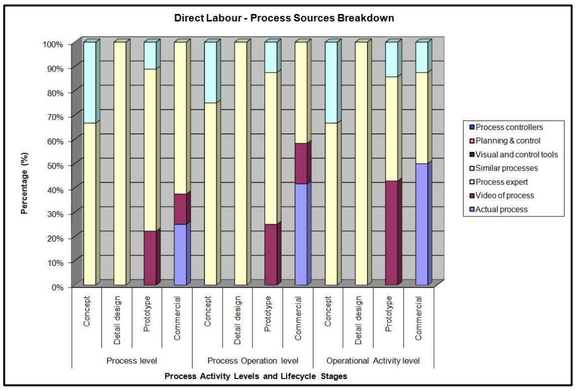

Figure C4.11 Process Sources Breakdown for Process Activities - Direct Labour

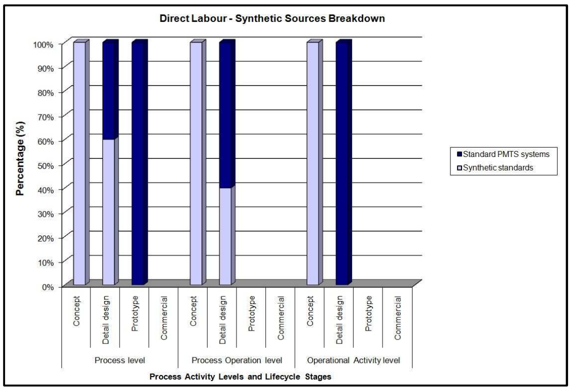

Figure C4.12 Synthetic Sources Breakdown for Process Activities - Direct Labour

Process Features

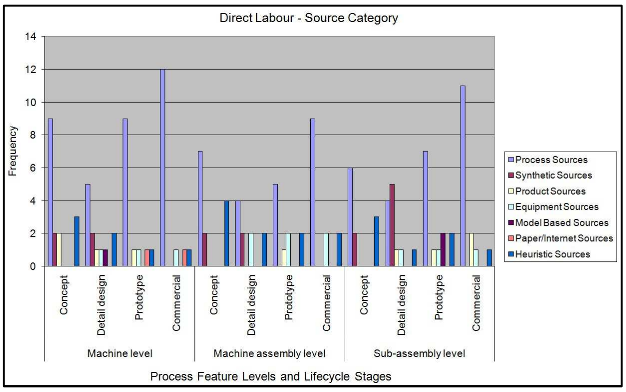

Figure C4.13 Data Sources of Process Features for Direct Labour

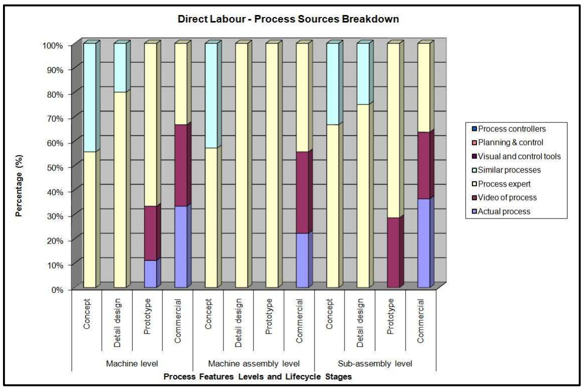

Figure C4.14 Process Sources Breakdown for Process Features - Direct Labour

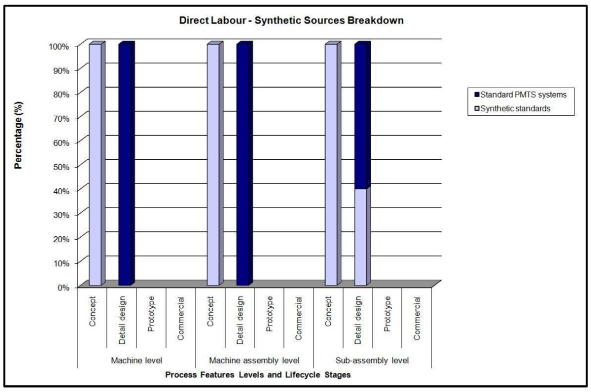

Figure C4.15 Synthetic Sources Breakdown for Process Features - Direct Labour

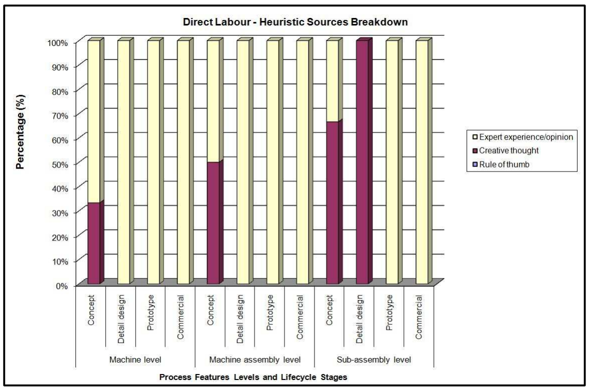

Figure C4.16 Heuristic Sources Breakdown for Process Features - Direct Labour

Product Features

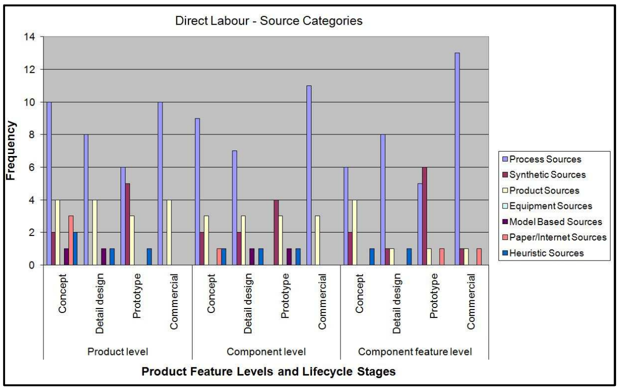

Figure C4.17 Data Sources of Product Features for Direct Labour

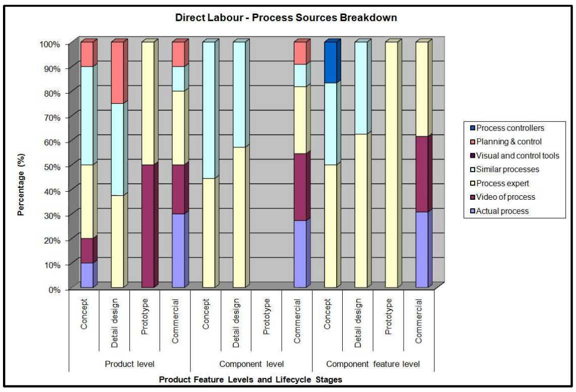

Figure C4.18 Process Sources Breakdown for Product Features - Direct Labour

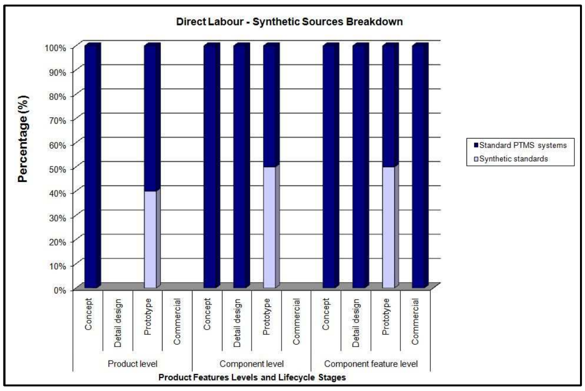

Figure C4.19 Synthetic Sources Breakdown for Product Features - Direct Labour

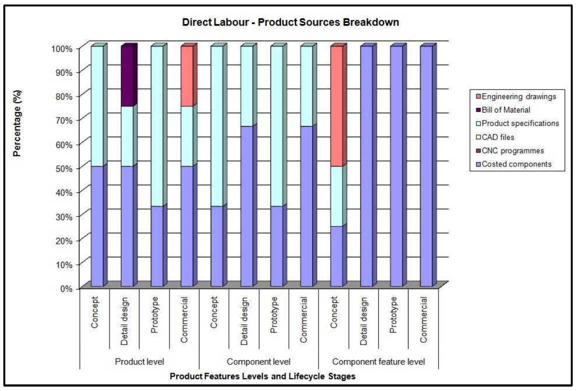

Figure C4.20 Product Sources Breakdown for Product Features - Direct Labour.

C4.3 Indirect Material Cost

Process Activities

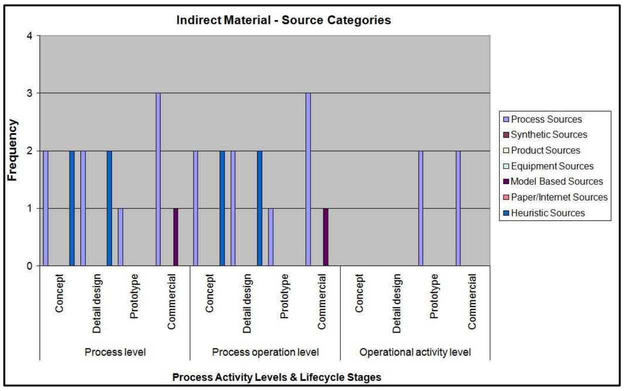

Figure C4.21 Sources of Process Activity data for Indirect Material

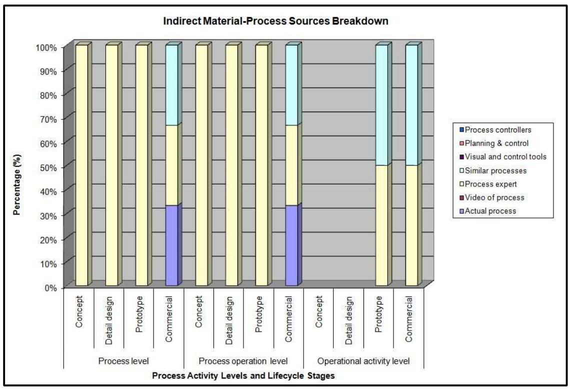

Figure C4.22 Process Sources Breakdown for Process Activities - Indirect Material

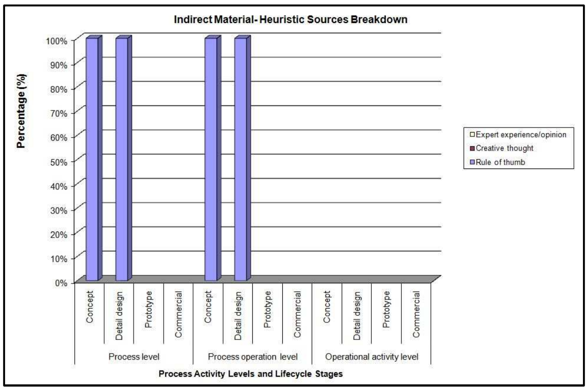

Figure C4.23 Heuristic Sources Breakdown for Process Activities - Indirect Material

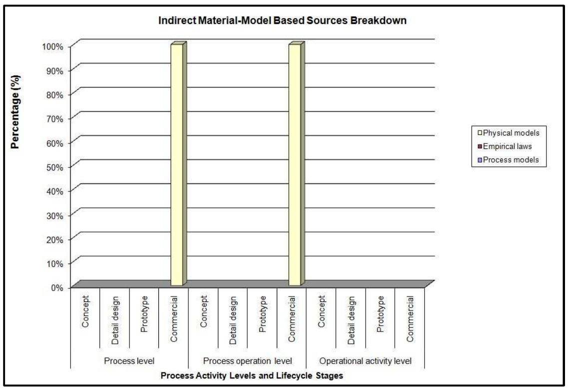

Figure C4.24 Model-based Sources Breakdown for Process Activities - Indirect Material

Process Features

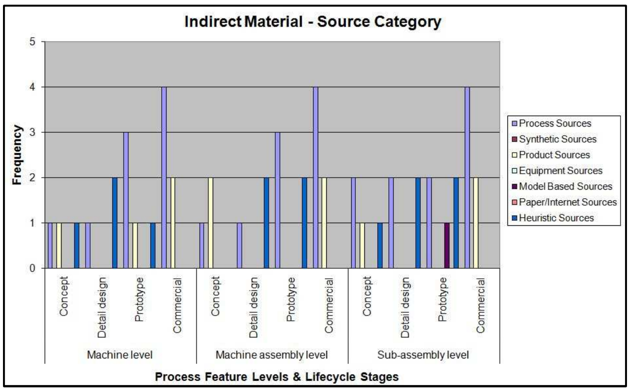

Figure C4.25 Sources of Process Feature data for Indirect Material

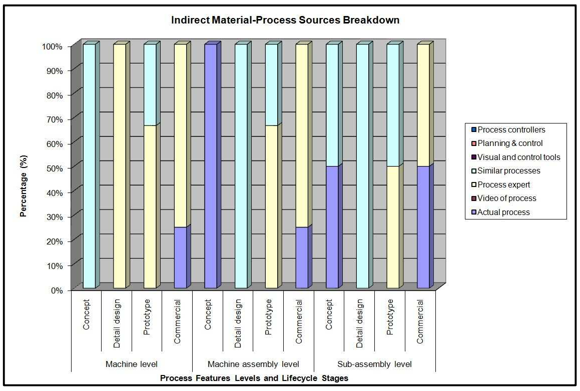

Figure C4.26 Process Sources Breakdown for Process Features - Indirect Material

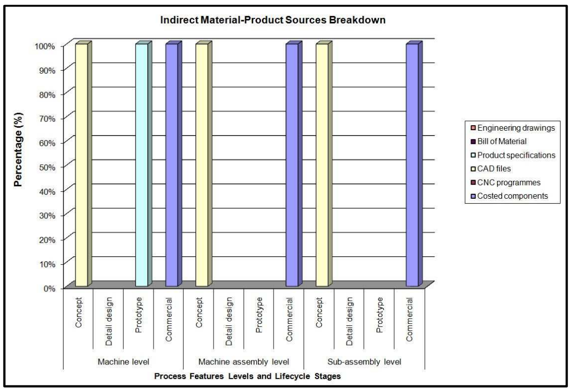

Figure C4.27 Product Sources Breakdown for Process Features - Indirect Material

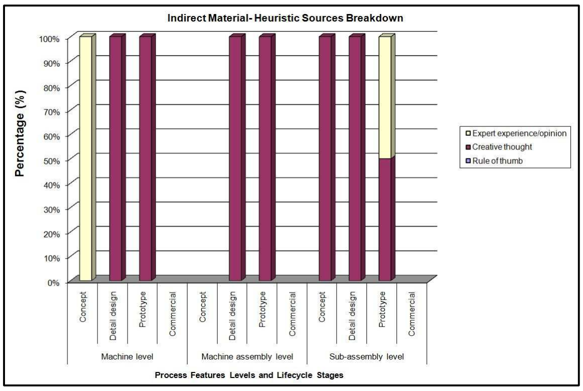

Figure C4.28 Heuristic Sources Breakdown for Process Features - Indirect Material

Product Features

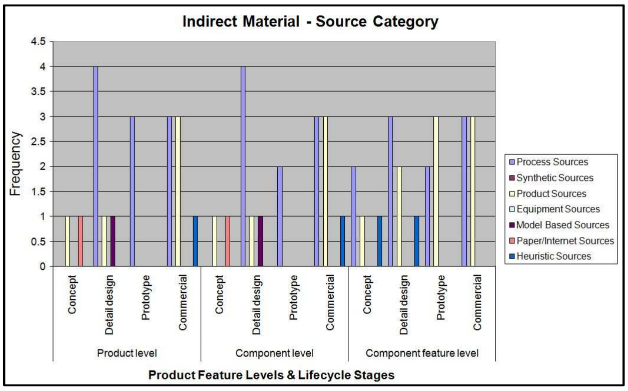

Figure C4.29 Sources of Product Feature data for Indirect Material

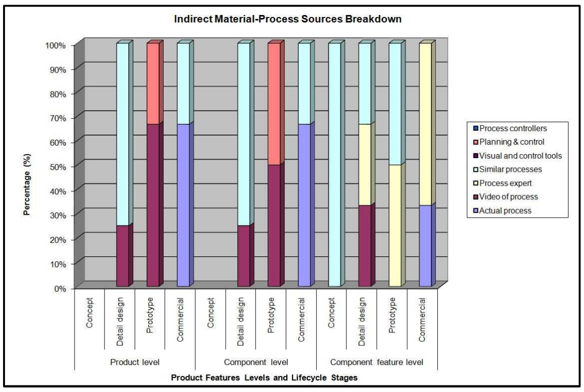

Figure C4.30 Process Sources Breakdown for Product Features - Indirect Material

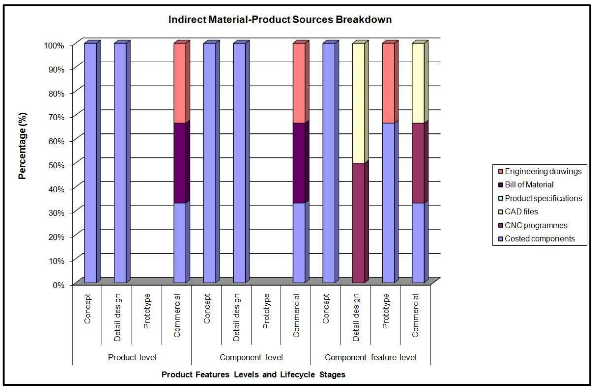

Figure C4.31 Product Sources Breakdown for Product Features - Indirect Material

C4.4 Indirect Labour Cost

Process Activities

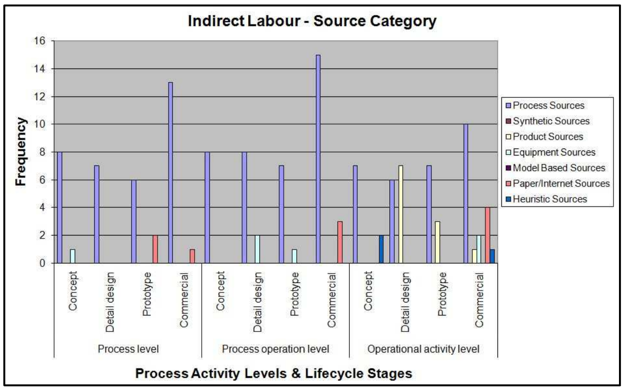

Figure C4.32 Sources of Process Activity data for Indirect Labour

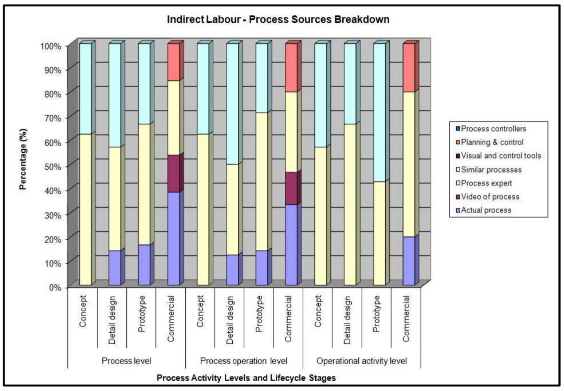

Figure C4.33 Process Sources Breakdown for Process Activity - Indirect Labour

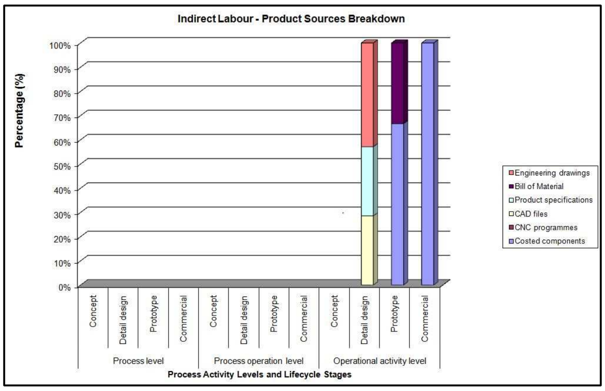

Figure C4.34 Product Sources Breakdown for Process Activity - Indirect Labour

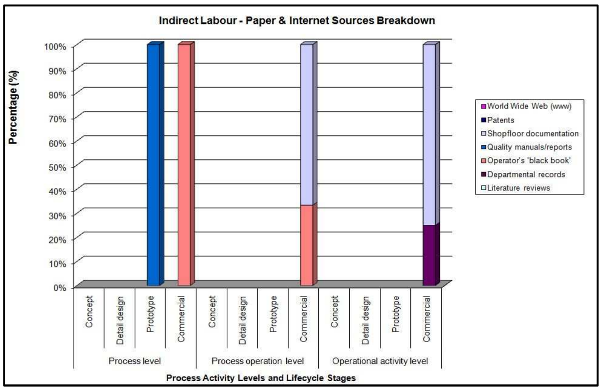

Figure C4.35 Paper and Internet based Sources Breakdown for Process Activity - Indirect Labour

Process Features

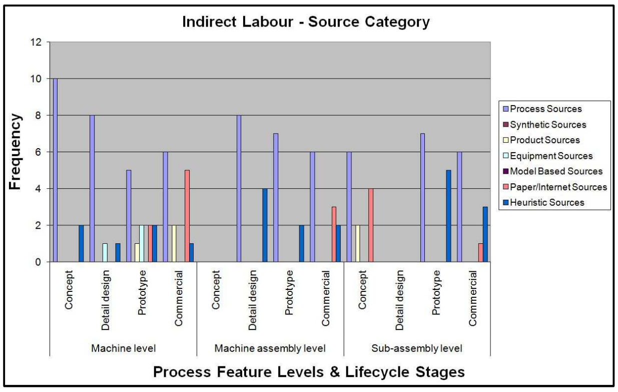

Figure C4.36 Sources of Process Feature data for Indirect Labour

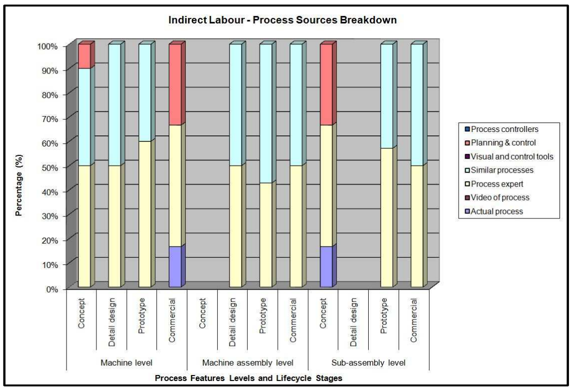

Figure C4.37 Process Sources Breakdown for Process Features - Indirect Labour

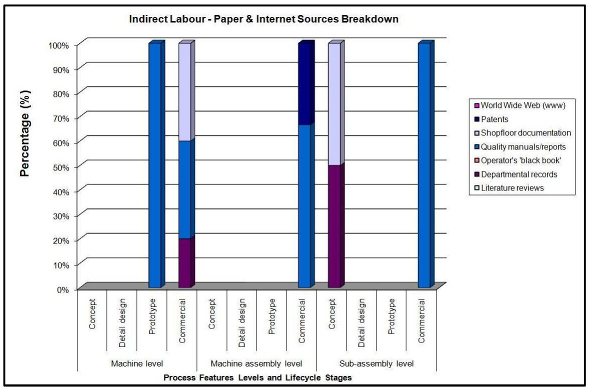

Figure C4.38 Paper-based and Internet Sources Breakdown for Process Features - Indirect Labour

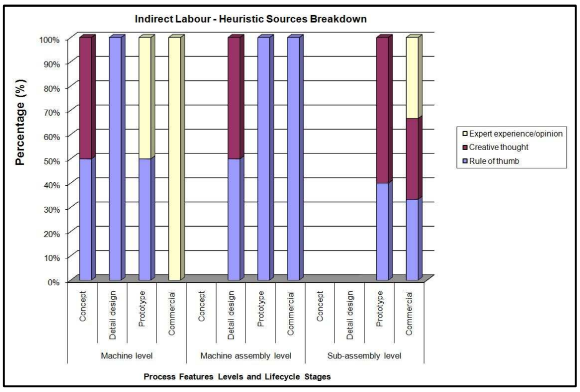

Figure C4.39 Heuristic Sources Breakdown for Process Features - Indirect Labour

Product Features

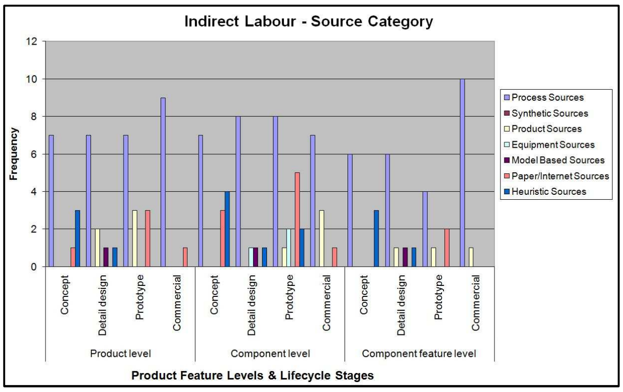

Figure C4.40 Sources of Product Features for Indirect Labour

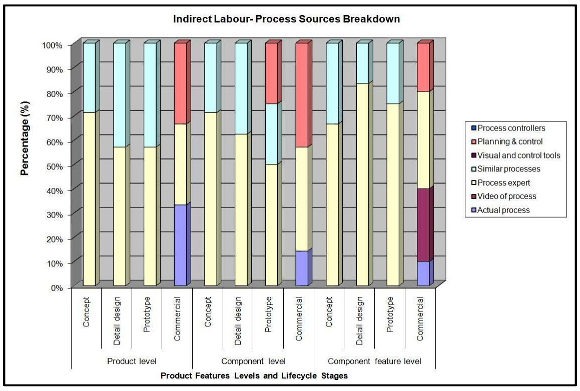

Figure C4.41 Process Sources Breakdown for Product Features - Indirect Labour

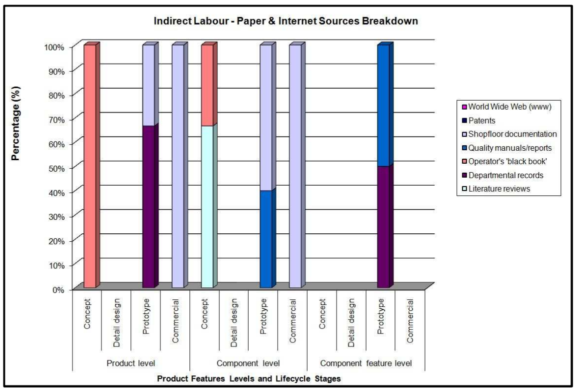

Figure C4.42 Paper-based & internet Sources Breakdown for Product Features - Indirect Labour

C4.5 Manning Levels

Process Activities

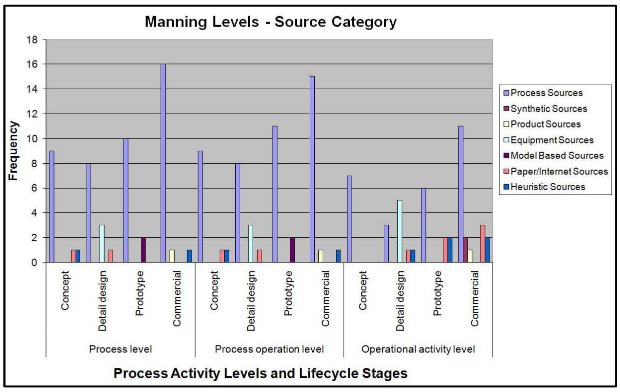

Figure C4.43 Sources of Process Activity data for Manning Levels

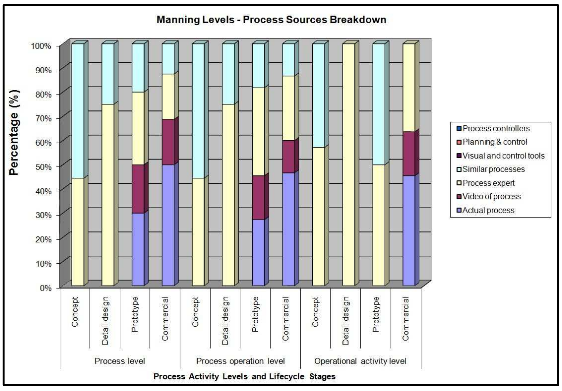

Figure C4.44 Process Sources Breakdown for Process Activity – Manning Levels

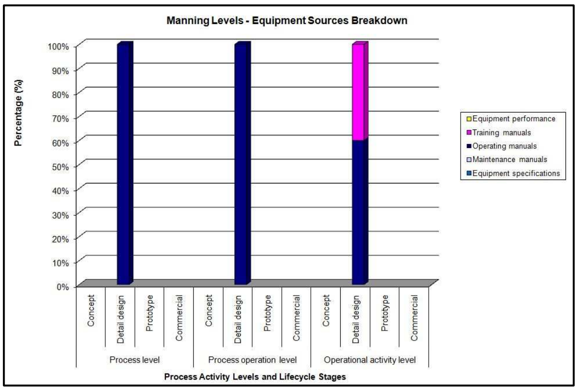

Figure C4.45 Equipment Sources Breakdown for Process Activity – Manning Levels.

Process Features

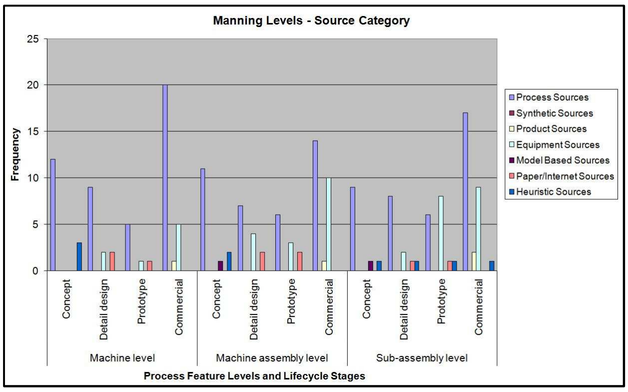

Figure C4.46 Sources of Process Feature data for Manning Levels

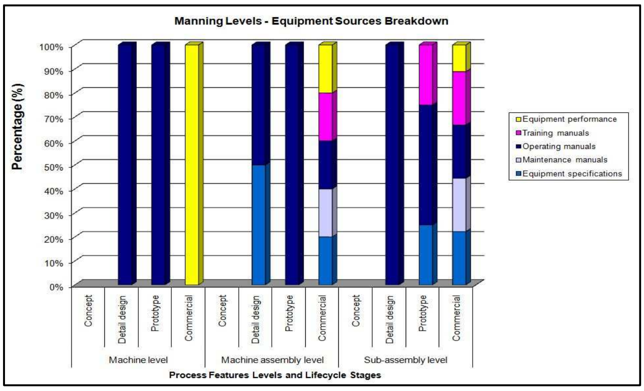

Figure C4.47 Equipment Sources Breakdown for Process Features – Manning Levels

Product Features

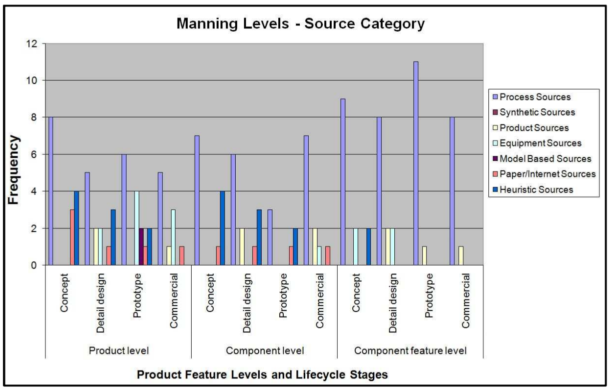

Figure C4.48 Sources of Product Feature data for Manning Levels

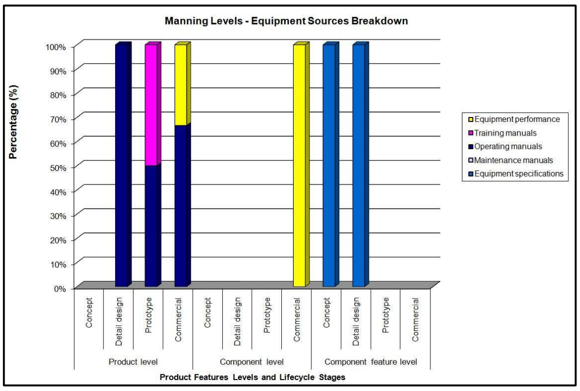

Figure C4.49 Equipment Sources Breakdown for Product Features – Manning Levels.

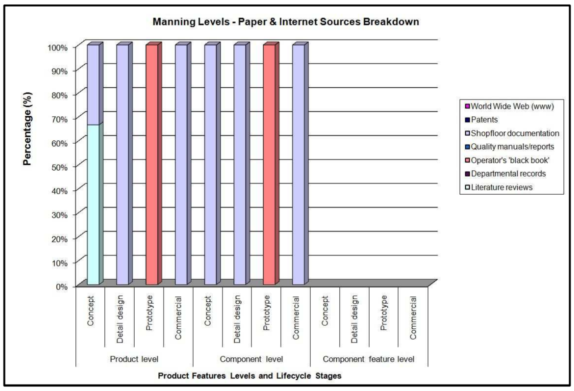

Figure C4.50 Paper and Internet based Sources Breakdown for Product Features – Manning Levels

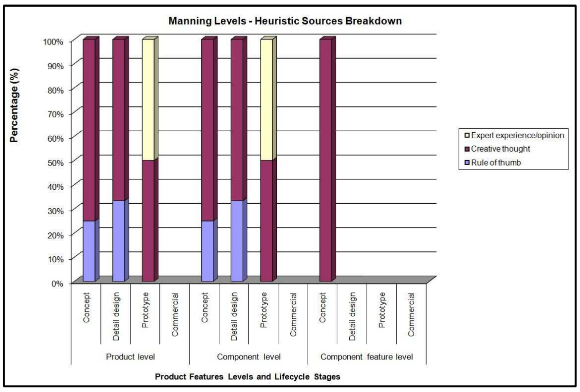

Figure C4.51 Heuristic Sources Breakdown for Product Features – Manning Levels

C4.6 Process Time

Process Activities

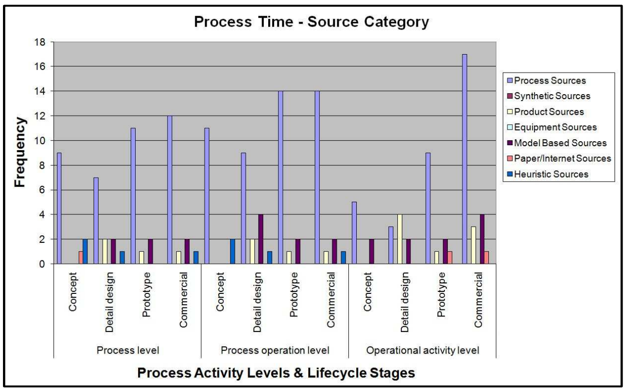

Figure C4.52 Sources of Process Activity data for Process Time

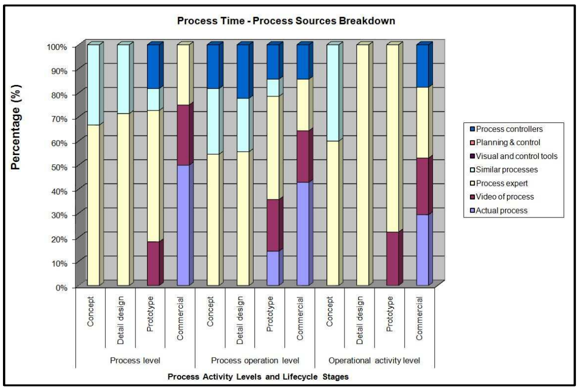

Figure C4.53 Process Sources Breakdown for Process Activity – Process Time

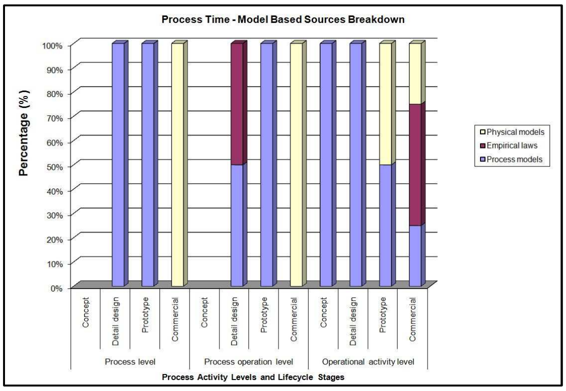

Figure C4.54 Model based Sources Breakdown for Process Activity – Process Time

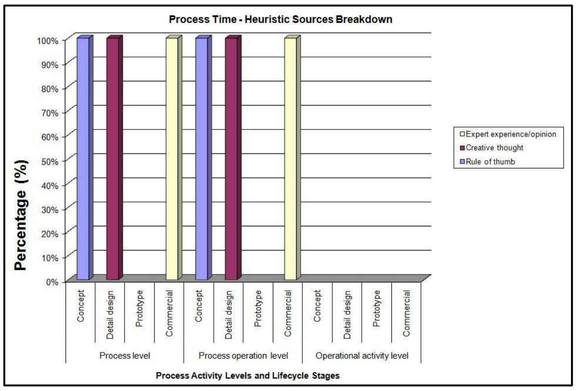

Figure C4.55 Heuristic Sources Breakdown for Process Activity – Process Time

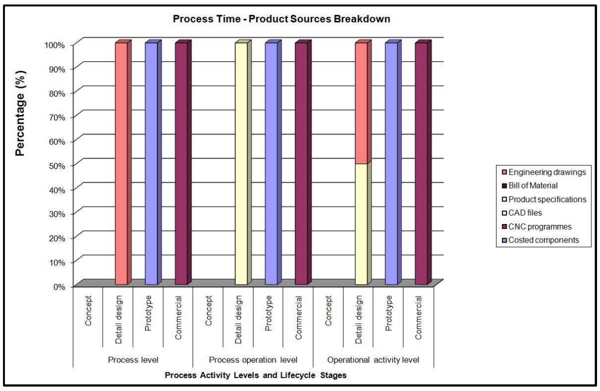

Figure C4.56 Product Sources Breakdown for Process Activity – Process Time

Process Features

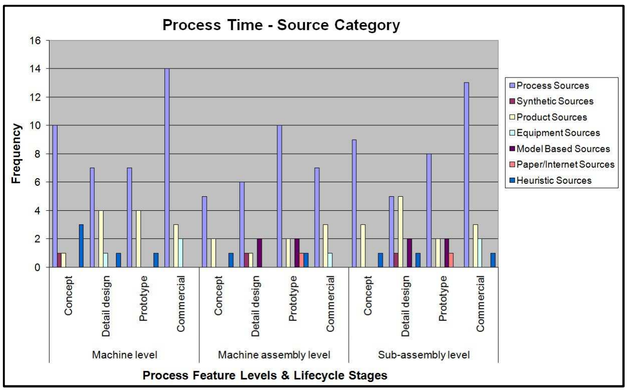

Figure C4.57 Sources of Process Feature data for Process Time

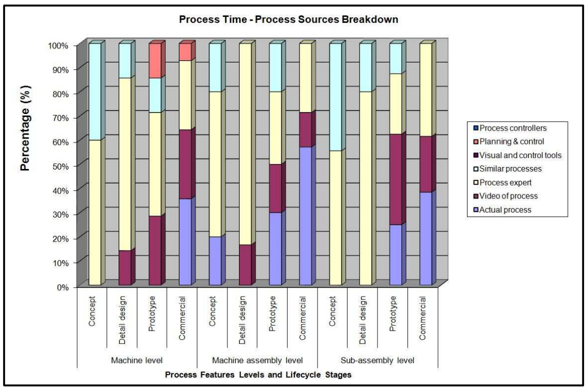

Figure C4.58 Process Sources Breakdown for Process Feature – Process Time

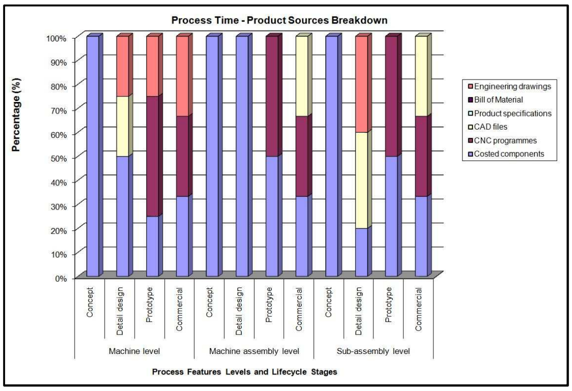

Figure C4.59 Product Sources Breakdown for Process Feature – Process Time

Product Features

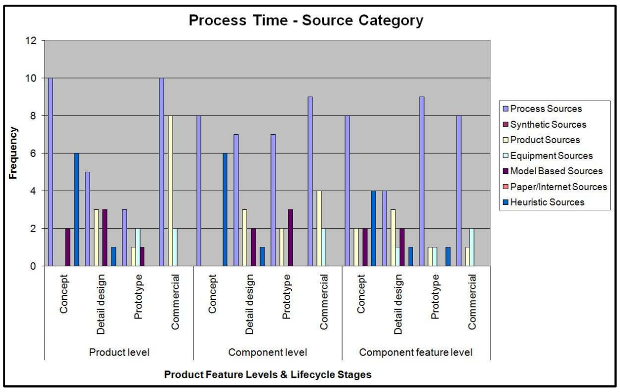

Figure C4.60 Sources of Process Feature data for Process Time

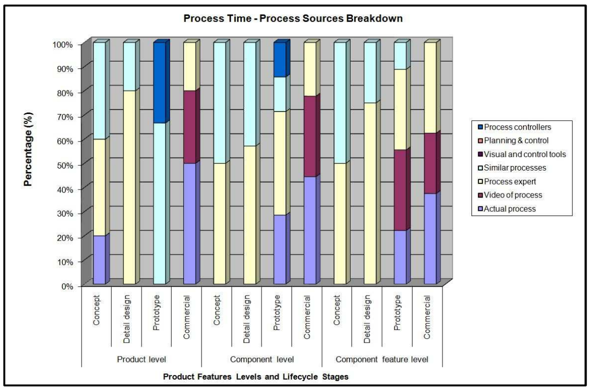

Figure C4.61 Process Sources Breakdown for Product Feature – Process Time

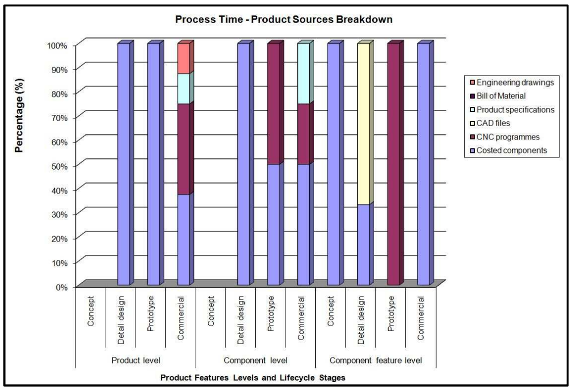

Figure C4.62 Product Sources Breakdown for Product Feature – Process Time

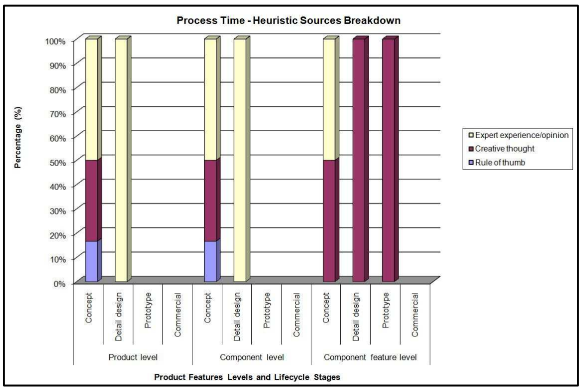

Figure C4.63 Heuristic Sources Breakdown for Product Feature – Process Time

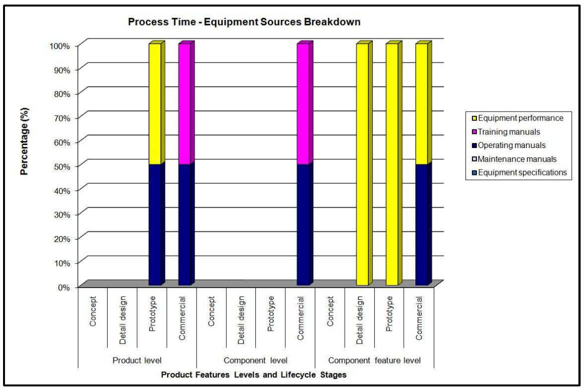

Figure C4.64 Equipment Sources Breakdown for Product Feature – Process Time

C4.7 Elapsed Time

Process Activities

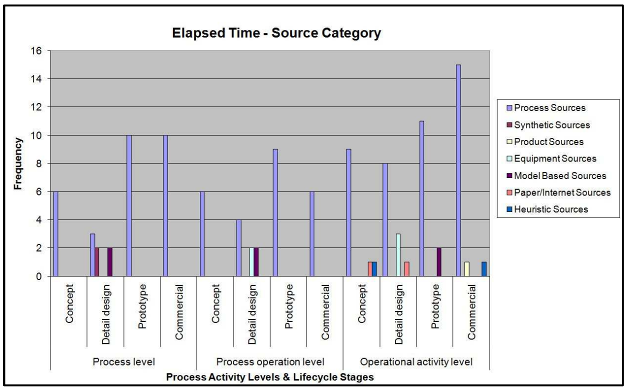

Figure C4.65 Sources of Process Activity data for Elapsed Time

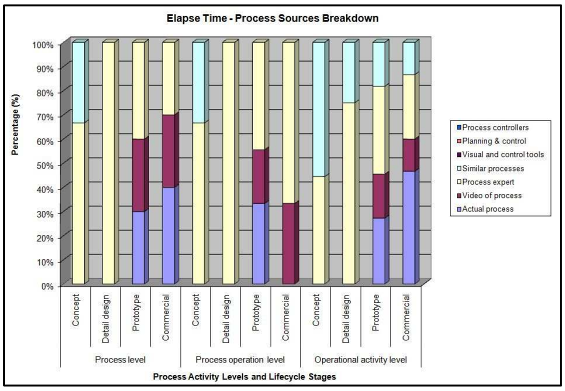

Figure C4.66 Process Sources Breakdown for Process Activity – Elapsed Time

Process Features

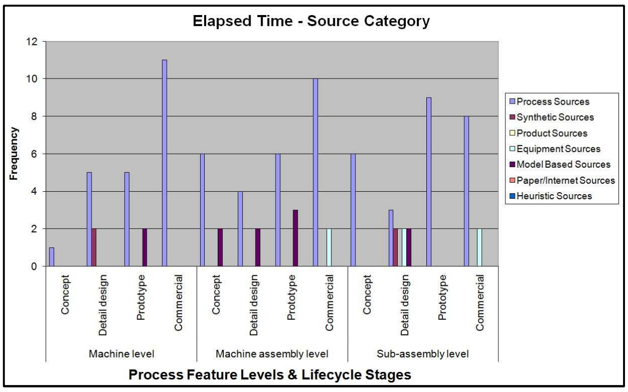

Figure C4.67 Sources of Process Feature data for Elapsed Time

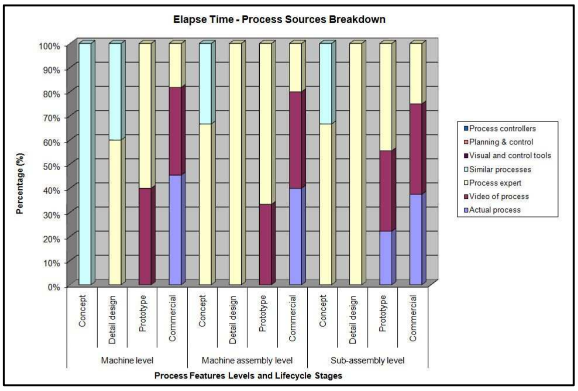

Figure C4.68 Process Sources Breakdown for Process Feature – Elapsed Time

Product Features

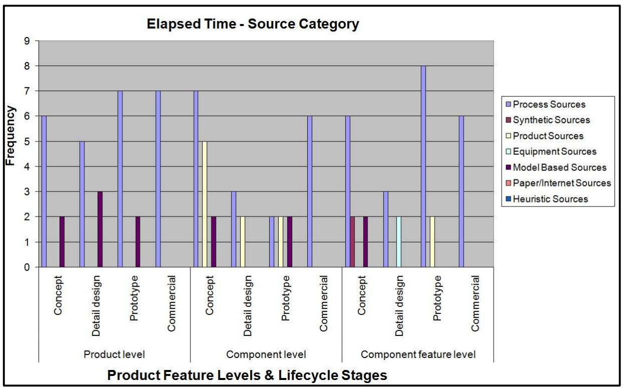

Figure C4.69 Sources of Product Feature data for Elapsed Time

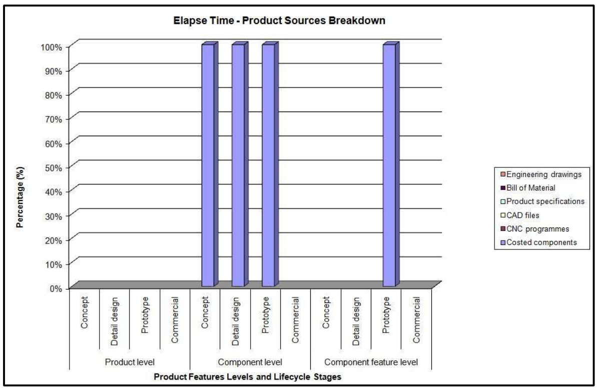

Figure C4.70 Product Sources Breakdown for Product Feature – Elapsed Time

C4.8 Tooling

Process Activities

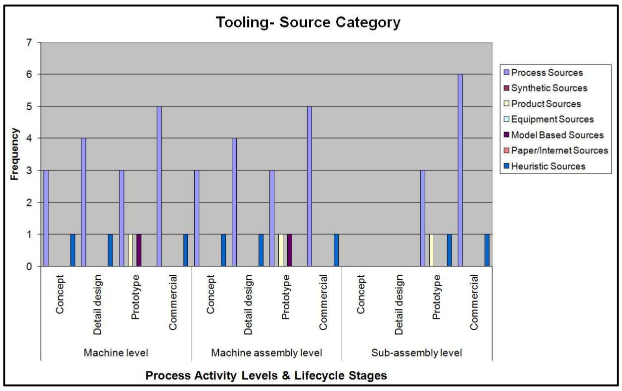

Figure C4.71 Sources of Process Activity data for Tooling

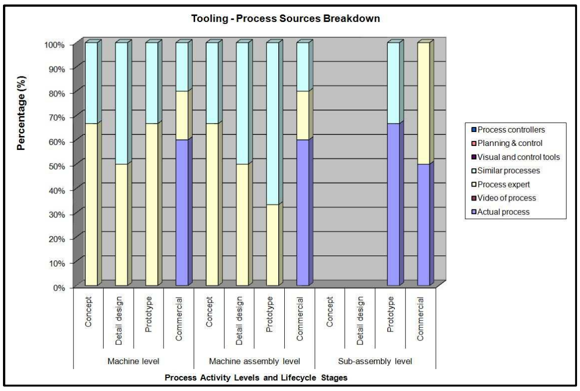

Figure C4.72 Process Sources Breakdown for Process Activities – Tooling

Process Features

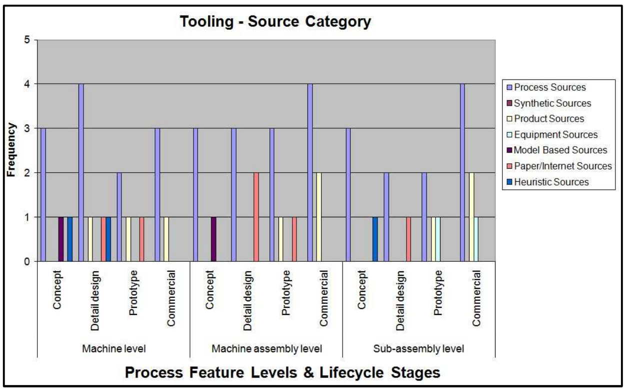

Figure C4.73 Sources of Process Feature data for Tooling

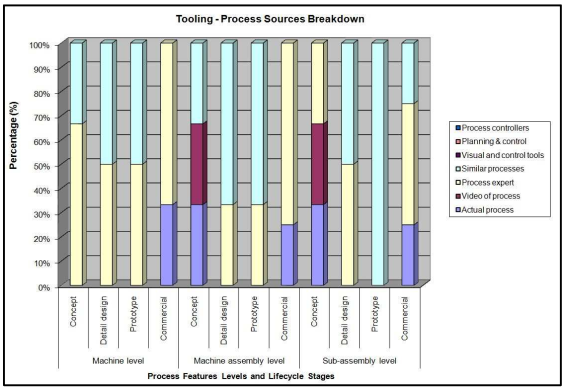

Figure C4.74 Process Sources Breakdown for Process Features – Tooling

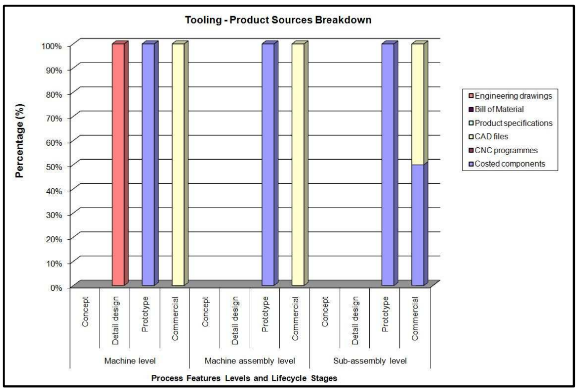

Figure C4.75 Product Sources Breakdown for Process Features – Tooling

Product Features

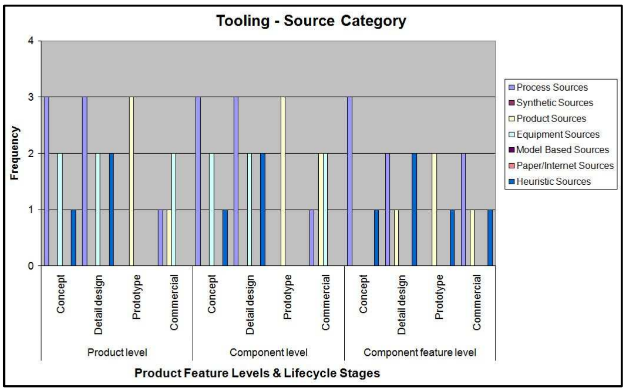

Figure C4.76 Sources of Process Feature data for Tooling

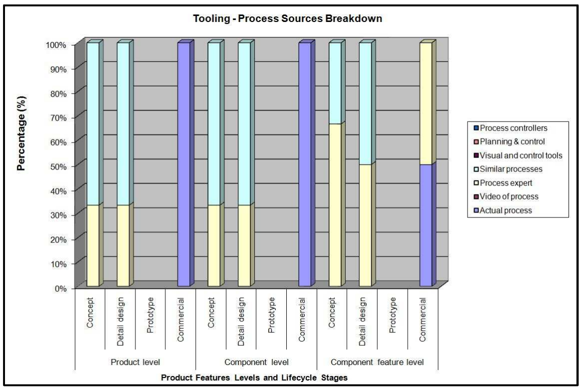

Figure C4.77 Process Sources Breakdown for Product Features – Tooling

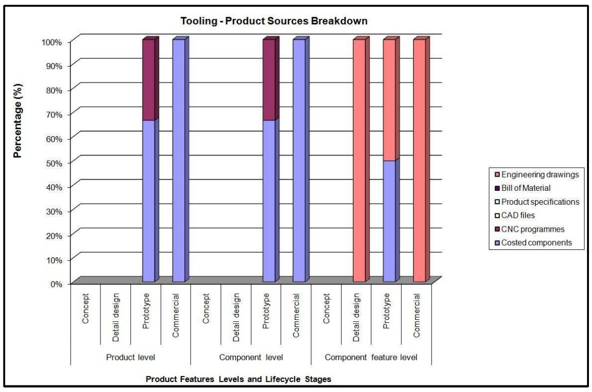

Figure C4.78 Product Sources Breakdown for Product Features – Tooling

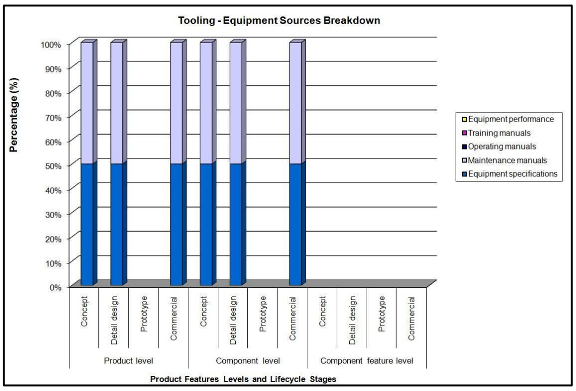

Figure C4.79 Equipment Sources Breakdown for Product Features – Tooling

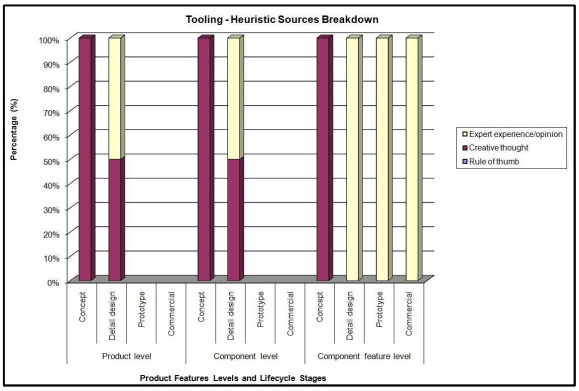

Figure C4.80 Heuristic Sources Breakdown for Product Features – Tooling

APPENDIX D: COST MODEL SCOPING FRAMEWORK

D1 CMSF – Case Study 2: Double Diaphragm Forming (DDF)

Model Scoping Framework

I. PROCESS INFORMATION

1. Please provide information regarding the following:

Process Name:	Double Diaphragm Forming (DDF)
Process Functions:	Manufacturing of Spars, and possibly Ribs.
Personnel involved, i.e. Process Owner:	[redacted] (RA) (Manufacturing Engineering) (SW) (Manufacturing Engineering)

2. Identify the development state of the process and/or process equipment - established, new, under development. Please tick (√) as appropriate.

Process/equipment	Concept	Detail Design	Prototype	Commercial
Modified DDF process	√			
Diaphragm Preparation			√	
General Manufacture			√	

3. List the main products/components that require this process and their respective product life cycle stage. Please tick (√) as appropriate.

Product	Name	Concept	Detail Design	Prototype	Commercial
Product 1	Spars				√
Product 2	Ribs				√
Product 3					
Product 4					

1

4. Identify the type of processing system to be employed. Please tick (√) as appropriate.

	Flow Process	Batch Production	Job Shop	Project
High volume				
Medium to low volumes				
Small volumes/one off				

5. Identify the working environment that the process forms part of - succeeding process, preceding process, working practices

The preceding process is the preparation of the preform. The succeeding process is machining, which takes place when the component is formed and cured. Afterwards, the next step is the assembly process.

The model will just include the Double Diaphragm Forming process and the machining of the component profile.

6. Identify the owners of data (product, process, environment, accounting, cost engineering etc)

Technical data regarding the process: [redacted] (RA) and [redacted] (SW).

Information regarding the Cost Model: [redacted] (MD), [redacted] (MR).

2

II. COST MODEL INFORMATION

1. Identify the Business Objectives & Decision Levels, applicable to the cost models. Please tick (√) as appropriate.

	Strategic	Tactical	Operational
Cost reduction		√	
Process time reduction		√	
Process evaluation	√		
Process improvement		√	
Process development	√		
Product evaluation		√	
Product improvement		√	
Product development	√		
Standard data generation		√	
Capacity planning			
Production scheduling			
Pricing and/or quotations			
Business planning			
Investment planning			
Procurement decisions			
Manufacturing decisions		√	
Others:			

3

2. Identify the cost model characteristics in terms of:

Model Owner: (including job title, and years of experience)	[redacted] (MR), Cost Engineering – Composite Wing Project [redacted] (RA), Manufacturing Engineering – Composite Wing Project
Model Developer: (including job title, and years of experience)	[redacted] (MR), Cost Engineering – Composite Wing Project
Model User: (including job title, and years of experience)	The model will be used by people from the manufacturing and cost engineering functions. [redacted] (RA), Manufacturing Engineering – Composite Wing Project [redacted] (SW), Manufacturing Engineering – Composite Wing Project
Function of the model	To determine the estimating time for the manufacturing of wing components (spars) using the Double Diaphragm Forming process. This model will be used as a trade off tool.
Level of Precision	The model is required to be highly precise, however, as before, this characteristic will be difficult to determine.
When the model needs to be used?	The process is in its concept stage. The time scale for the model is the end of this year, i.e. the model has to be completed by [redacted].
How long is the model to be used for? Time scale.	As long as the process is used for the manufacturing of the component.

Estimating Accuracy (in terms of the deviation from the actual value of the cost being estimated). Please tick (√) as appropriate.	Lower than 5%	5%	10%	15%	20%	25%	Higher than 25%
						√	

Comments:

The product/process resources that the cost model has to estimate are Equipment, Labour, Material, and Consumables, i.e. all recurring cost aspects of the process. Tooling, jigs and fixtures are excluded.

The main costs related to the process are **Material (i.e. fibre) > Man-hours > Consumables (i.e. seals, diaphragm, rubber bags, etc).** Tooling will not be included.

There is no interest in the accounting aspect of the development of the model. The respective accounting factors and cost rates will be used internally at BAE Systems, Airbus once the model is ready and running. The use of the proper currency and cost rates vary from one situation to another depending on the circumstances around it and the rules and terms that apply to each particular situation.

5. Identify the available sources of data on the process and products, if known. Please tick (√) as appropriate.

Sources of data	Process	Products
Actual Process	√	
Video of Process		
Process Expert	√	√
Synthetic Standards		
Costed Components		
Standard PTMS Systems		
Similar Processes		
Creative Thought	√	
Literature reviews	√	
Equipment Specification	√	
Maintenance Manuals		
Operating Manuals		
Training Manuals		
Process Models (1)	√	
Physical Models		
CNC Programmes		
Departmental records (2)		
CAD Files		
Operator's Black Book		
Quality manuals/reports		
Equipment performance		
Product Specification		√
Engineering Drawings	√	√
Empirical Laws	√	
Process Controllers (3)	√	
Planning & Control Sheets		
Photographic techniques		
Shopfloor Documentation		
Patents	√	
Others:		

Comments:

The information available in terms of process times, etc is based on trials done at a laboratory scale. There is not data available at production level (i.e., Departmental records, CAD files, Costed components, Operating manuals, Operator's 'black book', Quality manuals/reports, Equipment performance, Shopfloor documentation, etc), because the process has not been implemented yet.

Some sources of data available, which were identified, are the Internet, other company's reports, brochures and books, cost models from similar processes, etc. It was mentioned that data related to operation times, etc is first extract from these sources of information, instead of being collected from the actual process which has not been implement yet.

Theses, internet, www, company brochures and books count among the sources used in the literature review.

Notes:
(1) Software/paper based models of the process
(2) Manufacturing & accounting reports, data. E.g. labour cost rates, batch size, annual demand, payback periods for capital equipment.
(3) E.g. Temperature controllers, etc

7

D2 CMSF – Case Study 3: Five Axes CNC Machine Station

Model Scoping Framework

I. PROCESS INFORMATION

1. **Please provide information regarding the following:**

Process Name:	CNC Mitsui Small Hard Metal Machine Centre (single spindle horizontal machining centre). Model [redacted]
Process Functions:	Manufacturing of small hard metal components (for the [redacted])
Personnel involved, i.e. Process Owner:	[redacted], Manufacturing

2. Identify the development state of the process and/or process equipment - established, new, under development. Please tick (√) as appropriate.

Process/equipment	Concept	Detail Design	Prototype	Commercial
CNC M/C Centre			√	

3. List the main products/components that require this process and their respective product life cycle stage. Please tick (√) as appropriate.

Product	Name	Concept	Detail Design	Prototype	Commercial
Product 1	General (small hard metal components)			√	
Product 2					
Product 3					
Product 4					

1

4. **Identify the type of processing system to be employed. Please tick (√) as appropriate.**

	Flow Process	Batch Production	Job Shop	Project
High volume				
Medium to low volumes		√		
Small volumes/one off				

5. **Identify the working environment that the process forms part of - succeeding process, preceding process, working practices**

Some parts, which require higher tolerances, go off line. They are taken to other machining centres for boring or drilling operations (i.e. post-processes).

Pallets pools are used to minimise lead times. These allow machining up to 10 components on one side, and then 10 more on the other side.

6. **Identify the owners of data (product, process, environment, accounting, cost engineering etc)**

Manufacturing Function

2

II. COST MODEL INFORMATION

1. Identify the Business Objectives & Decision Levels, applicable to the cost models. Please tick (√) as appropriate.

	Strategic	Tactical	Operational
Cost reduction		√	
Process time reduction			
Process evaluation		√	
Process improvement			
Process development		√	
Product evaluation			
Product improvement		√	
Product development		√	
Standard data generation			
Capacity planning			
Production scheduling			
Pricing and/or quotations		√	
Business planning		√	
Investment planning	√		
Procurement decisions		√	
Manufacturing decisions		√	
Others:			

3

2. Identify the cost model characteristics in terms of:

Model Owner: (including job title, and years of experience)	[redacted]
Model Developer: (including job title, and years of experience)	[redacted]
Model User: (including job title, and years of experience)	Engineers within multi-discipline teams.
Function of the model	To generate a Cost Estimating Relationship (CER) for calculating the man/hours related to the tasks performed in the manufacturing of small hard metal. This is a specific model for a particular machining operation.
Level of Precision	
When the model needs to be used?	
How long is the model to be used for? Time scale.	As this is a development process significant learning should result in many process improvements. Such unstable processes should be reviewed at least once every 12 months.

Estimating Accuracy (in terms of the deviation from the actual value of the cost being estimated). Please tick (√) as appropriate.	**Lower than 5%**	**5%**	**10%**	**15%**	**20%**	**25%**	**Higher than 25%**

4

3. Briefly describe the process tasks for which cost model(s) need to be developed. Please tick (√) as appropriate.

Main Process Tasks involved	Name	Concept	Detail Design	Prototype	Commercial	New Process	Modified Process
Task 1							
Task 2							
Task 3							
Task 4							
Task 5							

4. Identify the product and process resources that the cost model must estimate (machines, handling and process equipment, labour, tooling, materials, data requirements, overheads, jigs & fixtures)

Resources & Level of Cost data required. (Including recurring and non-recurring costs). Please tick (√) as appropriate.

		Material/ equipment	Direct Labour	Indirect Labour	Process time	Elapsed time	Manning level
Product Feature Costs							
Level 1	Product level	√					
Level 2	Component level						
Level 3	Component Feature level						
Process Feature Costs							
Level 1	Machine level						
Level 2	M/C assembly level						
Level 3	Sub-assembly level						
Process Activity Cost							
Level 1	Process Level				√		√
Level 2	Process operation level						
Level 3	Operational activity level						

Comments:

This is a high level model. Data available consist of a small sample of component masses, and cycle times recorded, machine standard documents, and machine and component drawings. The number of input variables should be kept to a practical minimum.

Operational cost and cost rates will not be included. Some cost drivers and product features will be based on qualitative data rather than numerical. Three elements will be considered as ***output*:** **Conventional hours, NC hours (man/hrs), and Material Cost (£).**

For the CER the important elements are **man/hours, and machine operation times**. **Non-recurring costs, actual process times**. After the man-hours are obtained, the charging rates will be included internally at [redacted]

Unloading and loading activities, tooling, jigs and fixtures will not be included. For set-up and handling there is some data available in the form of Standard Times.

5. Identify the available sources of data on the process and products, if known. Please tick (√) as appropriate.

Sources of data	Process	Products	Comments:
Actual Process	√	√	There is no historical data or time watch information available. However there is some recorded data in terms of operating times (feeds and speeds).
Video of Process			
Process Expert	√	√	
Synthetic Standards	√	√	
Costed Components	√(*)	√(*)	In two months time some recorded data will be available.
Standard PTMS Systems			
Similar Processes	√	√	
Creative Thought			There is no high complexity involved. Titanium is used as raw material for the manufacture of the components.
Literature reviews			
Equipment Specification	√		
Maintenance Manuals			
Operating Manuals			(*) (timed)
Training Manuals			
Process Models (1)			
Physical Models			
CNC Programmes			
Departmental records (2)			
CAD Files	√	√	
Operator's Black Book			
Quality manuals/reports			
Equipment performance			
Product Specification		√	
Engineering Drawings	√	√	
Empirical Laws			
Process Controllers (3)			
Planning & Control Sheets	√		
Photographic techniques			
Shopfloor Documentation			
Patents			
Others:			

Notes:
(1) Software/paper based models of the process
(2) Manufacturing & accounting reports, data. E.g. labour cost rates, batch size, annual demand, payback periods for capital equipment.
(3) E.g. Temperature controllers, etc

7

Model Scoping Framework

I. PROCESS INFORMATION

1. Please provide information regarding the following:

Process Name:	Rear Flange Manufacturing (O-Ring).
Process Functions:	The metal removal, metal cutting, metal shaping and metal finishing of O-rings
Personnel involved, i.e. Process Owner:	Manufacturing Engineering

2. Identify the development state of the process and/or process equipment - established, new, under development. Please tick (√) as appropriate.

Process/ Equipment	Concept	Detail Design	Prototype	Commercial
All M/C and equipment				√

3. List the main products/components that require this process and their respective product life cycle stage. Please tick (√) as appropriate.

Product	Name	Concept	Detail Design	Prototype	Commercial
Product 1	Rear Flange				√
Product 2	Other rings (*)				√
Product 3	Cases				√

(*) With the same basic function, but which differ in size and material. All rings use the same type of operations, but following a different sequence.

1

4. **Identify the type of processing system to be employed. Please tick (√) as appropriate.**

	Flow Process	Batch Production	Job Shop	Project
High volume				
Medium to low volumes		√		
Small volumes/one off				

5. **Identify the working environment that the process forms part of - succeeding process, preceding process, working practices**

The main tasks of the process include:

Pre-Process: Handling, Loading and Machine Set-up
General cleaning of the machine

Process: Cycle & Machining
On line inspection

Post-Process: Unloading
Off line inspection
Post-process (off line) Machining Set-up

6. **Identify the owners of data (product, process, environment, accounting, cost engineering etc)**

Manufacturing Engineering: [redacted]
Design Engineering: [redacted].
Cost Engineering: [redacted].

2

II. COST MODEL INFORMATION

1. Identify the Business Objectives & Decision Levels, applicable to the cost models. Please tick (√) as appropriate.

	Strategic	Tactical	Operational
Cost reduction	√		√
Process time reduction			√
Process evaluation			√
Process improvement			√
Process development			√
Product evaluation			√
Product improvement			√
Product development			√
Standard data generation			
Capacity planning			√
Production scheduling			√
Pricing and/or quotations			√
Business planning			
Investment planning			
Procurement decisions			√
Manufacturing decisions			√
Others:			
Bid Analysis			√
Cost/Weight Trade Off			√
Target Cost			√
Should Cost			√
Life/Cost Trade			√

3

2. Identify the cost model characteristics in terms of:

Model Owner: (including job title, and years of experience)	
Model Developer: (including job title, and years of experience)	
Model User: (including job title, and years of experience)	Design (cheapest design solution), Manufacturing Engineers (to evaluate the way of producing the component), and Cost Engineers (to assess the cheapest and effective way of producing the component) I WOULD NOT IMAGINE DESIGN ENGINEERS TO USE THE MODEL
Function of the model	To produce the Unit Cost of the component or feature being evaluated. To identify the high cost features of the design.
Level of Precision	High consistency is required. Otherwise the confidence in the model will be lost.
When the model needs to be used?	2 to 3 months to gather the necessary information. 2 months to develop a high level model 6 to 12 months for a very detailed model, i.e. for individual manufacturing operations.
How long is the model to be used for? Time scale.	The model should be used until a change in the technology being employed is introduced. The model has to be as flexible as possible, and also adaptable.

Estimating Accuracy (in terms of the deviation from the actual value of the cost being estimated). Please tick (√) as appropriate.	**Lower than 5%**	**5%**	**10%**	**15%**	**20%**	**25%**	**Higher than 25%**

(*) The level of detail of the input data is high. It includes all detailed process for O-rings, including detailed operations for the manufacturing of rear flanges: Turning, Grinding, Milling, etc.

3. Briefly describe the process tasks for which cost model(s) need to be developed. Please tick (√) as appropriate.

Main Process Tasks involved	Name	Concept	Detail Design	Prototype	Commercial	New Process	Modified Process
Task 1							
Task 2							
Task 3							
Task 4							
Task 5							

4. Identify the product and process resources that the cost model must estimate (machines, handling and process equipment, labour, tooling, materials, data requirements, overheads, jigs & fixtures)

Resources & Level of Cost data required. (Including recurring and non-recurring costs). Please tick (√) as appropriate.

		Material/ equipment	Direct Labour	Indirect Labour	Process time	Elapsed time	Manning level
Product Feature Costs							
Level 1	Product level	√					
Level 2	Component level	√					
Level 3	Component Feature level	√					
Process Feature Costs: Milling M/C							
Level 1	Machine level	√					√
Level 2	M/C assembly level						
Level 3	Sub-assembly level						
Process Activity Cost: Operations							
Level 1	Process Level		√		√		
Level 2	Process operation level		√		√		
Level 3	Operational activity level		√		√		

5

Comments:

The total time of the operations will be the criteria for ranking each task.

Cost drivers will be the activities with the longest times. (NO HIGHEST COST , NOT LONGEST TIME i.e. Hand Process long time but low charge rates , High Technology , short time but high charge rates. Cost Drivers are measured in £ and not hours.

5. Identify the available sources of data on the process and products, if known. Please tick (√) as appropriate.

Sources of data	Process	Products	Comments:
Actual Process	√	√	
Video of Process			
Process Expert	√	√	
Synthetic Standards		√	
Costed Components		√	
Standard PTMS Systems			
Similar Processes	√	√	
Creative Thought	√	√	
Literature reviews	√		
Equipment Specification	√		
Maintenance Manuals	√		
Operating Manuals	√		
Training Manuals			
Process Models (1)			
Physical Models			
CNC Programmes	√		
Departmental records (2)	√	√	
CAD Files	√	√	
Operator's Black Book			
Quality manuals/reports	√		
Equipment performance			
Product Specification			
Engineering Drawings		√	
Empirical Laws			
Process Controllers (3)			
Planning & Control Sheets			
Photographic techniques			
Shopfloor Documentation		√	
Patents			
Others:			

Notes:
(1) Software/paper based models of the process
(2) Manufacturing & accounting reports, data. E.g. labour cost rates, batch size, annual demand, payback periods for capital equipment.
(3) E.g. Temperature controllers, etc

7

APPENDIX E: LIBRARY OF DC-TTMS, DS AND DATA TYPES - SAMPLES

Method: Delphi method

References: Gerald Nadler, Work Design - A Systems concept, Richard D. Irwin, pp.193-204
ISBN 085012

Function: To form an opinion or consensus without an actual physical meeting taking place.

Inputs: Expert opinion elicited by questionnaire.

Outputs: A ranked set of data by importance in an ordinal fashion.

Personnel: Teams of engineers, for example, with manufacturing experience, whom have the questionnaires sent to them.

Equipment: Paper, pencil, set cards or PC based software used to automate the process.

Environment: The Delphi method may be used in any environment where work is undertaken, e.g. manufacturing, distribution, office, but is not restricted by location.

Sequence:

Assemble a team and design a questionnaire to be distributed among the participants.
The questionnaires are refined as the process continues. The first may generate a set of alternatives that are considered and ranked in a second round of questioning.
Further processing of the data can occur through other data analysis methods though not losing sight of the original subjectivity of the data.

A. Data Types	
x	activity descriptions
x	resource descriptions
x	activity times
x	resource times
x	resource costs
x	manpower requirements
x	activity dependencies
x	task sequences
x	accounting data
x	equipment operating data

B. Data Sources			
	actual process	x	departmental records
	video of process		CAD files
x	process expert	x	operator's 'black book'
	synthetic standards		quality manuals/reports
	costed components		equipment performance
	standard PMTS systems		product specifications
	similar processes		engineering drawings
x	creative thought	x	empirical laws
x	literature reviews		process controllers
	equipment specifications		planning & control
	maintenance manuals		shopfloor documentation
	operating manuals		
	training manuals		
	process models		
	physical models		
	CNC programmes		

Comments: A variety of advantages exist with the Delphi method. Without direct face to face meetings the participants do not introduce psychological or sociological bias into their responses. Time is saved and the response is not limited to time scales of meetings or localities.

Method: Direct observation

References: Gerald Nadler, Work Design - A Systems concept, Richard D. Irwin, pp.193-204
ISBN 085012
LCCC No 7011417

Function: To collect data and elicit knowledge using possibly other formal methods to do so.

Inputs: An actual process and set of experts

Outputs: A set of data of differing types and formats.

Personnel: Engineers with some manufacturing experience, though this not necessary.

Equipment: Paper, pencil and stop watch

Environment: Observation may be used in any environment where work is undertaken, e.g. manufacturing, distribution, office

Sequence:

1. Assemble formalised methods and formats into which the data is to be collected into. Data identification procedures should already have provided what is to be collected

2. Observe the process and discuss as much as possible with the experts and engineers the objectives of the exercise. In such a manner learning may occur.

	A. Data Types
x	activity descriptions
x	resource descriptions
x	activity times
x	resource times
x	resource costs
x	manpower requirements
x	activity dependencies
x	task sequences
	accounting data
x	equipment operating data

	B. Data Sources		
x	actual process		departmental records
x	video of process		CAD files
x	process expert	x	operator's 'black book'
	synthetic standards	x	quality manuals/reports
	costed components	x	equipment performance
	standard PMTS systems		product specifications
x	similar processes	x	engineering drawings
	creative thought		empirical laws
	literature reviews		process controllers
	equipment specifications		planning & control
	maintenance manuals		shopfloor documentation
x	operating manuals		
x	training manuals		
	process models		
x	physical models		
	CNC programmes		

Comments:

Method: Flow Diagram

References: Currie, R. M., Work Study, Pitman Publishing,
ISBN 0273009591

Function: It shows location of the various activities involved in an operation/process with respect to departments, working areas and their sequence. It is associated with a particular man, material or equipment FPC.

Inputs: Processes, operations, tasks and/or activities categorised as operation, transportation, inspection, delay, storage and/or hold. Inputs (area layout, distances, sequence and type of activities, etc) can be identified by visual observation or by judgement during design of a process.

Outputs: Diagram substantially to scale of the working area, illustrating the specific operations/activities (identified by their numbered symbols) of a process carried out and their sequence, and the routes followed by workers, materials or equipment in their execution. It can be used at different levels of detail, i.e., process level, process operation level, activity/task level.

Personnel: Engineers with manufacturing experience who have been trained to use the process flow technique.

Equipment: Paper, pencil

Environment: It may be used in any environment where work is undertaken, e. g., manufacturing, distribution, office, warehousing, etc.

Sequence:

1. Draw a scale layout of the area in which the subject(s) involved is (are) to move.

2. Indicate on the layout the areas where operations take place.

3. Use appropriate symbol to indicate the type of operation that is taking place, including a brief description of the operation or activity.

4. Draw lines from one operation area to another to indicate the sequence of operations involved.

5. The routes followed in transport are shown by joining the symbols in sequence by a line which represents as nearly as possible the paths of movement of the subject (worker, equipment, material) concerned.

6. The numbered transport symbols, which form part of the flow line, have to show direction of movement.

A. Data Types

x	activity descriptions
x	resource descriptions
	activity times
	resource times
	resource costs
	manpower requirements
x	activity dependencies
x	task sequences
	accounting data
x	equipment operating data

B. Data Sources

x	actual process	x	departmental records
x	video of process		CAD files
x	process expert	x	operator's 'black book'
	synthetic standards		quality manuals/reports
	costed components		equipment performance
	standard PMTS systems		product specifications
x	similar processes		engineering drawings
x	creative thought		empirical laws
	literature reviews		process controllers
x	equipment specifications	x	planning & control
	maintenance manuals	x	shopfloor documentation
x	operating manuals		
x	training manuals		
x	process models		
x	physical models		
	CNC programmes		

Comments:

Method: IDEF process charting

References: David A Marca, Clement L McGowan, SADT structured analysis and design technique, ISBN 0-07-040235-3

Function: Provides a set of formal background for building a process model.

Inputs: Any processes, operations, tasks, data and/or activities.

Outputs: Three layer model describing the process from a perspective and function that are predefined.

Personnel: An engineer with manufacturing experience who has been trained to use the IDEF modelling technique.

Equipment: Paper and pen or PC based modelling software. The latter is more preferable as it can be integrated into further stages of the cost modelling effort.

Environment: IDEF modelling may be used in any safe environment where work is undertaken, eg manufacturing, distribution, office

Sequence:

State the function of the model, and the perspective from which the model is being built. For example, "Develop a time estimate for manufacturing process X from the perspective of an industrial engineer."
There are three levels of detail and abstraction on which to build the model. Levels A0 through to A1.
Each process can be modelled or depicted by boxes into which four arrows are input and output. These are called ICOM, input, output, control, and mechanism. The inputs say what goes into the process, the output says what leaves the process, the controls give the constraints of the process and the mechanism says how this is going to be completed.
The arrows show the flow of input and so on, and can be aggregated and disaggregated in the opinion of the process modeller.
A comprehensive methodology of performing IDEF modelling is available in the above reference.
The number of boxes is limited between five and six to encourage simplicity.
Authors for official review and commentary prepare Kits. In this way models can be validated.
Certain heuristics and recommendations are available for building simplified process models.

A. Data Types	
x	activity descriptions
x	resource descriptions
x	activity times
x	resource times
x	resource costs
x	manpower requirements
x	activity dependencies
x	task sequences
x	accounting data
x	equipment operating data

B. Data Sources			
x	actual process	x	departmental records
x	video of process	x	CAD files
x	process expert	x	operator's 'black book'
x	synthetic standards	x	quality manuals/reports
x	costed components	x	equipment performance
	standard PMTS systems	x	product specifications
x	similar processes	x	engineering drawings
x	creative thought	x	empirical laws
x	literature reviews		process controllers
x	equipment specifications	x	planning & control
x	maintenance manuals	x	shopfloor documentation
x	operating manuals		
x	training manuals		
x	process models		
x	physical models		
x	CNC programmes		

Comments: IDEF modelling aids and promotes understanding and hence could be considered helpful within the data identification stages.

Method: MOST (Maynard Operation Sequence Technique)

Function: MTM method derived from MTM1 in order to simplify and accelerate application without loss of accuracy. It identifies 8 key activities, which occur in three fixed sequences.

Inputs: Description of the task and sequence of the activities involved, each work element performed (in the form of a range of body movements or 'basic motions') by the operator/worker. And any other incidents and activities which occur during the study. All this data is collected by the observer, while he/she watches the task being performed.

Outputs: MOST sheet form which contains detailed record of all the elements necessary for the completion of the task, described in the form of basic motions and their respective times (expressed in TMU's).

Personnel: Personnel: Engineers with manufacturing experience who have been trained to use this work measurement technique. It is required to undertake a recognised training course and to pass a certifying examination to be able to practise it. The training is provided by MTM associations, which respond to the International MTM Directorate.

Equipment: Paper, pencil, MOST forms and MOST tables. Stopwatch is not used when applying MTM except to time machine speeds and machine controlled elements. Standard rating is not overtly used.

Environment: It may be used in any environment where work is undertaken, e. g. manufacturing, distribution, office, warehousing, etc.

References: Currie, R. M., Work Study, Pitman Publishing, ISBN 0273009591

Sequence:
1. Get all details and information concerning the job to be measured. Data is gathered either by direct observation of the motions used and their times, while the tasks are being performed, or by using synchronous cine-camera equipment.
2. Rate the operators while the film record is being made, in order to bring the times for all motions to a common level.
3. Break the job down into recognisable pieces called work elements.
4. Construct time for job. The time value in MTM is determined by the nature of the motions and the conditions under which they are made (i.e., the variables that affect the motions). The basic time of the motions is expressed in Time Measurement Units (TMU's). One TMU is one hundred thousandth part of 1 hr (i.e., about 1/28th of a second).
5. Stopwatch timings and ratings assessments are built into the MOST tables. All MTM tables have built in rating assessment of 83 on the BSI 0-100 scale. Usually the MTM time is adjusted (multiplying by 83 and dividing by 100) to produce the equivalent of a basic time.
6. Determine allowances for fatigue, personal needs, working conditions, etc.
7. Calculate standard time for job. MTM data can be fed into a computer along with the basic motions considered to be necessary and the computer will deliver the best sequence, allocate the movements to right and left hands and calculate the job time in TMU's.

A. Data Types	
x	activity descriptions
x	resource descriptions
x	activity times
x	resource times
	resource costs
x	manpower requirements
x	activity dependencies
x	task sequences
	accounting data
x	equipment operating data

B. Data Sources			
x	actual process		departmental records
x	video of process		CAD files
x	process expert	x	operator's 'black book'
x	synthetic standards		quality manuals/reports
	costed components		equipment performance
	standard PMTS systems		product specifications
x	similar processes		engineering drawings
	creative thought		empirical laws
x	literature reviews	x	process controllers
	equipment specifications	x	planning & control
	maintenance manuals	x	shopfloor documentation
	operating manuals		
x	training manuals		
x	process models		
x	physical models		
	CNC programmes		

Comments: It is claimed that MOST is up to 40 times faster than MTM-1 and up to 15 times faster than MTM-2. It applies for very short, repetitive tasks.

Method: Networks, CPM and PERT

References: Joseph J. Moder, Cecil R. Phillips, Edward W. davis. Project management with CPM, PERT and precedence diagramming. Third Edition. ISBN 0-442-25415-6

Function: To record costs, times, and other forms of data within a network and node structure including probabilities and constraints. In such a manner, data is identified and categorised as well as rated.

Inputs: Times, costs, probabilities, subjective scoring

Outputs: Diagram illustrating the operations and their sequence which may include operation times. The method can be used at different levels of detail, i.e. process level, process operation level, activity/task level. Other outputs include ranked lists of data on an ordinal scale as well as ratings of listed time and cost constraints among others in order to sort and direct the data collection effort.

Personnel: Engineers with manufacturing experience who have been trained to use the CPM, PERT and network techniques. Proprietary software packages exist that are specifically designed for such an analysis, though spreadsheet based programs can also be constructed.

Equipment: Paper, pencil, Excel spreadsheet, and project management automated tools.

Environment: Project management techniques may be used in any environment where work is undertaken, e.g. manufacturing, distribution, or office environments.

Sequence:

Create a checklist of steps within the manufacturing process. This is the most important step allowing for planning and changes when the cost exercise is not yet fully committed by data collection.
The checklist may also be substituted for a graphical representation of the process in a nodal network format.
Utilise the objectives and constraints of the cost exercise and include within the network diagram or spreadsheet format of the PERT technique.
Elicit expert opinion on optimistic, pessimistic and most likely values for a quantity to be measured. This quantity maybe cost or time for example.
Use the PERT technique that is built on the Beta distribution to calculate a mean quantity as well as variance.
Enter a desired value for the quantity to be measured for each process step.
Assume the quantities are normally distributed and calculate probabilities that the desired values can be reached.

A. Data Types	
x	activity descriptions
x	resource descriptions
x	activity times
x	resource times
x	resource costs
x	manpower requirements
x	activity dependencies
x	task sequences
x	accounting data
x	equipment operating data

B. Data Sources			
x	actual process	x	departmental records
x	video of process		CAD files
x	process expert	x	operator's 'black book'
x	synthetic standards		quality manuals/reports
x	costed components		equipment performance
x	standard PMTS systems	x	product specifications
x	similar processes		engineering drawings
x	creative thought		empirical laws
x	literature reviews		process controllers
	equipment specifications	x	planning & control
	maintenance manuals		shopfloor documentation
x	operating manuals		
x	training manuals		
x	process models		
x	physical models		
	CNC programmes		

Comments: The objectives of the cost estimating effort and the perspective of the engineer are most important in determining the structure and values to be included within the network diagram. Precedence values can be uncertain and dealt with and supplanted by methods from outside of the project management techniques. Networking diagrams allow greater confidence in the ensuing modelling effort at an early stage. Simulations and probabilistic techniques are used within the above methods and can be used in a trial and error approach in identifying data. This can be thought of as a kind of sensitivity analysis in the early stage of a project, utilising possibly methods dealing with uncertainty such as fuzzy logic. Criticality indices can be calculated using sample sizes of between 400 and 10,000 in finding the best and most appropriate data to collect. QGERT is another project management technique that could be argued to be also a data collection method. Expert opinion is utilised along a network structure.

Method: Outline Process Chart

Function: Gives an overall view of a process by recording in sequence only the main operations and inspections.

Inputs: Processes, operations, tasks and/or activities categorised as operation, and inspection. Inputs (operation times and descriptions, inspection times and descriptions, sequence of activities involved, etc) can be identified by visual observation or by judgement during design of a process.

Outputs: Diagram or graphic representation of the points at which materials are introduced into a process, and of the sequence of all operations and inspections associated with the process.

Personnel: Engineers with manufacturing experience who have been trained to use the process flow charting technique.

Equipment: Paper, pencil and stopwatch.

Environment: It may be used in any environment where work is undertaken, e. g., manufacturing, distribution, office, warehousing, etc

References: Currie, R. M., Work Study, Pitman Publishing,
ISBN 0273009591

Sequence:

1. It must be decided in what detail operations are going to be recorded, and consistency must be shown throughout the chart.

2. Draw a scale layout of the area where the product or material is to move, indicating (on the layout) the areas where activities take place.

3. Use the appropriate symbols (operation and inspection) to indicate the type of activity that is taking place.

4. Record the time for each activity using a stopwatch.

5. Draw an arrow to indicate the entry of the main material or component, writing above the line a description of the component, and below a description of its condition.

6. Draw a line from one activity/operation involved to another using the appropriate symbols numbered in sequence, with a brief description to the right, and a note of the time taken to the left of the symbol for operations.

7. The major process is charted towards the right-hand side of the chart, and subsidiary processes are charted to its left. These subsidiary processes are joined to each other and to the main trunk at the place of entry of the materials or subassemblies.

8. When the chart is complete, it must be summarised. Operations and inspections are totalled (in minutes and seconds).

A. Data Types	
x	activity descriptions
	resource descriptions
x	activity times
	resource times
	resource costs
	manpower requirements
x	activity dependencies
x	task sequences
	accounting data
	equipment operating data

B. Data Sources			
x	actual process		departmental records
x	video of process		CAD files
x	process expert	x	operator's 'black book'
	synthetic standards		quality manuals/reports
	costed components		equipment performance
	standard PMTS systems		product specifications
x	similar processes		engineering drawings
x	creative thought		empirical laws
x	literature reviews		process controllers
x	equipment specifications	x	planning & control
	maintenance manuals	x	shopfloor documentation
	operating manuals		
	training manuals		
x	process models		
x	physical models		
	CNC programmes		

Comments: There are three typical formats for process charts designed to serve different purposes. They are Single Column Process Chart, Multicolumn Process Chart and Layout Diagram.
The Outline Process Chart is used as a preliminary investigation of the process, showing principal elements only, i.e. operations and inspections.

Method: Pair comparisons

References: Gerald Nadler, Work Design - A Systems concept, Richard D. Irwin pp. 193-204
ISBN 085012

Function: To compare a set of alternatives within a data set, mainly on a qualitative basis.

Inputs: Data set and qualitative comparisons, i.e. subjective scores from a set of experts.

Outputs: A data set with a corresponding frequency distribution based on an interval scale and not an ordinal scale.

Personnel: Engineers with manufacturing experience who have been trained to use pair comparisons. Specialised software exists that automates the process with a minimum effort required.

Equipment: PC based Windows software.

Environment: Pair comparisons may be used in any environment where work is undertaken, eg manufacturing, distribution, and office.

Sequence:

Choose a set of alternatives from a set of many, using possibly a data identification method.

Select a set of criteria, usually qualitative and subjective, the criteria is not usually a set of measured data, for example an actual set of cost data, though these can be used as a further set of data for comparative and probabilistic analysis.

Each pair comparison gives a winner and loser and a resulting frequency distribution that can be interpreted based on the criterion.

The frequency distribution can be used as the basis of producing some weightings.

A. Data Types	
x	activity descriptions
x	resource descriptions
x	activity times
x	resource times
x	resource costs
x	manpower requirements
x	activity dependencies
x	task sequences
x	accounting data
x	equipment operating data
x	all envisaged types

B. Data Sources			
x	actual process		departmental records
x	video of process		CAD files
x	process expert	x	operator's 'black book'
	synthetic standards		quality manuals/reports
	costed components		equipment performance
	standard PMTS systems		product specifications
	similar processes	x	engineering drawings
x	creative thought	x	empirical laws
x	literature reviews		process controllers
x	equipment specifications	x	planning & control
	maintenance manuals		shopfloor documentation
	operating manuals		
	training manuals		
x	process models		
x	physical models		
	CNC programmes		

Comments:

Method: Team Working	References: Schonberger, R and Knod, E (1994). Operations Management. Continuous Improvement. Fifth Edition. Richard Irwin Inc, Boston. ISBN 0-256-15602-6
Function: Total Quality Management Technique which brings together people from either the same or different levels, disciplines and/or departments within the organisation to build a team, which is trained in the use of problem-solving techniques and group dynamics methods. Inputs: Inputs come from team members (workers, operators, staff, managers, supervisors, etc) who collect data, suggest alternatives, and recommend course of action to be conducted. Outputs: problem identification, data and information regarding the process, task or activity under consideration, team members' suggestions for improvements, ideas, etc. Personnel: There is not restriction/requisites whatsoever for anyone to be involved in a working team as long as they are receptive to teambuilding efforts, receive the necessary training and skill requirements. Equipment: It uses other techniques such as process flowcharts, Pareto analysis, fishbone, brainstorming, etc to collect the required information. Environment: It may be used in any environment where work is undertaken, e g manufacturing, distribution, office, warehousing, government, service industry, etc	Sequence: 1. Get the right people into the team. Depending on the organisation, membership can be either voluntary or a part of everyone's job. 2. A facilitator provides training in process analysis and improvement, and may lead problem-solving team meetings. 3. Members study group dynamics methods, including brainstorming, nominal group techniques, role playing, multivoting, cohesiveness building, and consensus attainment as well as how to make presentations on proposed improvements. 4. An example of team working in the Aerospace Industry, it is the use of Integrated Product Teams (IPTs) in the Product Introduction Process. 5. These multidisciplinary teams are able to monitor their progress, meet cost targets for the final product as well as costs for realising the product. 6. These teams may involve people from different functions such as manufacturing, design, procurement, marketing and sales, research and development, finance, procurement, and cost engineering. 7. Cost engineers constitute an important element of support for the IPT, assuring that the cost estimate undertaken by the IPT is satisfactory, accurate, robust and valid; providing the tools and methods to collect and analyse the data, assessing procedures and influencing decisions, etc.

A. Data Types	
x	activity descriptions
x	resource descriptions
x	activity times
x	resource times
x	resource costs
x	manpower requirements
x	activity dependencies
x	task sequences
x	accounting data
x	equipment operating data

B. Data Sources			
x	actual process	x	departmental records
	video of process		CAD files
x	process expert		operator's 'black book'
x	synthetic standards		quality manuals/reports
x	costed components		equipment performance
x	standard PMTS systems		product specifications
	similar processes		engineering drawings
x	creative thought		empirical laws
	literature reviews	x	process controllers
	equipment specifications		planning & control
	maintenance manuals	x	shopfloor documentation
	operating manuals		
	training manuals		
	process models		
	physical models		
	CNC programmes		

Comments: